MULTIWAVELENGTH LASER PROPAGATION STUDY - - II

Interim Final Report
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SUMMARY

During the annual period covered by this report, a comprehensive, multiwavelength laser-beam propagation facility was completed and experiments were conducted over a horizontal, 1 mile path in order to investigate the adequacy of the commonly-used atmospheric model and to establish the wavelength-dependence of scintillations. The optical measurements included log amplitude variances, covariances, scintillation spectra, probability distributions, and receiver and transmitter aperture effects. The microthermal measurements included turbulence spectra, critical scales, and temperature probability distributions.

It was found that the inertial subrange model constitutes only an approximation to the true turbulence structure, and that the inner scale is often non-negligible. The prevalence of quasi-discrete inhomogeneities in the refractive index structure constant was verified, and the consequent difficulty in relating nonoptical "strength of turbulence" measurements to actual scintillations is pointed out. In spite of these inadequacies in the atmospheric model, it was found that the unsaturated multiwavelength scintillations compared reasonably well with theoretical predictions when based on the turbulence as determined from scintillations of a short-path, portable laser. Also, there was no indication of saturation of longer wavelengths at low variances relative to those for visible wavelengths. These and other tentative conclusions are discussed in detail.

The follow-on program is described, during which a series of comprehensive measurements will be made to establish further confidence in the tentative conclusions. Following this, certain other details will be investigated.

CONTENTS

I. INTRODUCTION AND CONCLUSIONS

During the annual period covered by this report, a comprehensive laser beam propagation facility was completed and experiments were conducted over a horizontal, 1 mile path in order to investigate the adequacy of the commonly-used atmospheric model and to establish the wavelength-dependence of scintillations. The measurements, many of which are discussed in the Quarterly Progress Reports,[1] were as follows:[2]

A. Log amplitude variances, covariances, spectra, and probability distributions taken simultaneously at 4880Å, 1.15μ, and 10.6μ wavelengths with virtual-point-source transmitters and real-time, analog data processing.

B. The refractive index structure constant, C_n^2, as determined by

   1. The variance of the temperature difference fluctuations between two fine-wire probes.

   2. The probability distribution of the temperature difference fluctuations.

   3. The scintillations due to a short-path, portable 6328Å (point-source) laser.

C. The spatial turbulence spectrum, and inner and outer scales, as determined from

   1. Temperature difference fluctuations as a function of probe separation

2. The spectra of temperature fluctuations as seen by a single probe.

D. The constancy (stationarity) of the degree of turbulence, as related to the presence of quasi-discrete "plumes" and a corresponding non-gaussian distribution of temperature fluctuations.

E. The degree of aperture-averaging of scintillations for a diffraction-limited receiver much larger than the transverse amplitude correlation length.

F. The effect of the transmitter aperture configuration on scintillations.

G. The relationship between broken cloud patterns and corresponding changes in the turbulence and scintillations.

The tentative conclusions reached from these experiments are as follows:

1. The turbulence is not locally uniform, and hence the probability distribution of temperature fluctuations is non-gaussian over any reasonable averaging time. Relative to the (unsaturated) optical and infrared scintillation levels, the value of C_n^2 determined directly from the variance of temperature difference is too high, while the value determined from the probability distribution (excluding the "wings" on gaussian probability paper) is too low.

2. The wavelength-dependence of unsaturated scintillations compares favorably with theory and with the value of C_n^2 inferred from the short-path laser, although with considerable data spread due to points #1 (above) and #4,5 (below).

3. There is no indication of a wavelength-dependence of saturation over this path; i.e., long wavelengths are not seen to saturate at low variances. This agrees with dimensional reasonings given in earlier reports.

4. The slope of the rms temperature fluctuations vs. frequency, on log-log paper, does not agree with the theoretical value of -5/6; and the slope of the variance of temperature-difference fluctuations vs. probe separation, also on log-log paper, does not agree with the theoretical value of 2/3. Also, these slopes vary from experiment to experiment. Consequently, the Kolmogorov (inertial subrange) model is incorrect or at best an approximation.

5. The "inner scale" of turbulence is nonnegligible under many conditions, and is typically of the order of 1 cm.

6. The "outer scale" of turbulence is on the order of 1/4 of the height, near the ground.

7. The theoretical covariance or transverse amplitude correlation length is usually near the value predicted by theory, but occasionally departs seriously. This effect relates to #'s 4, 5 above.

8. The agreement between scintillation spectra and covariances indicate that the "frozen-in" hypothesis is basically valid, although it can be of little utility if the wind is at a small angle relative to the line of propagation.

9. The scintillations at all wavelengths are log normal, within the accurate probability resolution range of these experiments.

10. The aperture-averaging of scintillations is much less successful than would be assumed from the summation of N independent, log-normal variables. This remains a mystery, since simultaneous covariance measurements show no residual log amplitude correlation for transverse points separated well beyond the correlation length.

11. The variance of (unsaturated) scintillations is larger for a finite, defocused transmitter than for a small or virtual-point-source aperture. This is opposite to the expected result for a focused or collimated aperture, and is important in interpreting experimental results in the literature.

12. The turbulence and corresponding scintillation increases by as much as an order of magnitude when the sun emerges from a cloud, indicating an immediate turbulence effect from the absorption of solar energy by e.g. water molecules.

During the follow-on period, these tentative results will be tested by repeated experimentation, with sufficient data over a variety of conditions to establish confidence in the conclusions. These plans are further discussed in Section III.

The deficiencies in the existing theory may now be summarized as follows:

1. The turbulence (spatial) spectrum is variable, with corresponding implications on the wavelength and pathlength dependence of scintillations.

2. The inner scale is nonzero and can have a substantial effect on the scintillations. Some theoretical treatment of this effect appears in the literature.[3]

3. The structure constant C_n^2 varies abruptly due to the presence of parcels of warmer, more turbulent air. The theory does not adequately define the "optical strength of turbulence" from e.g. probability distributions of temperature difference fluctuations.

4. Continuing theoretical attempts to treat saturation of scintillations, i.e. beyond the Rytov range,[4,5] are not yet successful[6,7].

Many of these points will be discussed in greater detail in the next section.

II. RECENT EXPERIMENTS AND FURTHER DISCUSSION

During the final quarter of the period of this report, and preparatory to the onset of summer weather, we have conducted experiments in the turbulence structure *per se*. This was done in order to understand better the limitations of the theory, and to define those practical experimental measures which would better characterize the medium. The measures have been incorporated as part of the "standard runs" now being made (Sec. III). The experiments have resulted in the confirmation of Lawrence's basic observations[8] on nonstationarity or plumes, which exist even for highly uniform conditions and terrain. This phenomenon has also been reported by others.[9,11]

A. Plumes and the Effective Value of C_n^2

The phenomenon of warmer parcels of air, containing higher turbulence and moving with the wind, leads to quasi-discrete variations in C_n^2 over the path. This effect does not directly imply a non-Kolmogorov spectrum, and can be viewed as a multiplicative or modulating factor on all spectral components of the turbulence (and on C_n^2). The effect is manifested in single-probe temperature fluctuation data as slow, additive temperature increments (with scale sizes beyond the outer scale), with accompanying increases in the fast fluctuations. The corresponding temperature difference fluctuations between two probes do not show the additive effect, which is spatially filtered by the separation of the probes, but they show the appearance of greatly enhanced fast fluctuations ("spiking").

Sequential single- and two-probe temperature fluctuations are shown in Figs. 1 and 2. A particularly striking example of spiking is shown in Fig. 3. The changes in the variance of temperature difference fluctuations ($\langle \Delta T^2 \rangle \propto C_n^2$), as determined with a two-second averaging-time-constant, are shown in Fig. 4. It should be noted that the presence of spiking (or jumps in C_n^2) is not well correlated with normally-fluctuating wind velocities, as shown in Fig. 5.

It is interesting to note that the fluctuations in the rms spectral component of ΔT, contained in 1 Hz spectral windows centered respectively at at 2 Hz and 100 Hz, are not qualitatively different in their time scales. This is shown in Fig. 6, and supports the model of a purely multiplicative or modulating effect due to the plumes.

In Lawrence's recent data,[8] the changes in temperature fluctuations were strikingly discrete, and he suggests a model whereby C_n^2 var between two definite levels. For our terrain, which is not as perfectly uniform, the situation appears more complicated.

Probability distributions of temperature-difference fluctuations are nongaussian, due to the plumes or nonstationary behavior. These distribution points may be taken sequentially, with long time constants, resulting in data which may reflect a monotonic diurnal trend. We have instead recorded the temperature fluctuations for a five minute period on magnetic tape, and then taken a number of discrete probability points, with 100 second time constants, from this "common time window". An example is shown in Fig. 7a. The long tails are manifestations of high-turbulence regions. In all cases, the slope taken from the middle of the curve gives a value for C_n^2 which is too low relative to unsaturated scintillations, while the true variance ($<\Delta T^2>$) including the tails gives a C_n^2 which is too high--usually by an order of magnitude.

Short-term, real-time probability curves are randomly distorted versions of the true distribution, with slopes which will vary from curve to curve but which usually predict too small a value for C_n^2. Such distributions are illustrated in Fig. 7b.

In Figs. 8 and 9, we compare values of C_n^2 as obtained from (1) short-term probability slopes,(2) the true variance $<\Delta T^2>$, and (3) short-path optical scintillations.

We are therefore left with the problem of determining the effective $<\Delta T^2>$ or C_n^2 from a scintillation standpoint, from data such as the curve of Fig. 7a. This problem needs urgent theoretical attention. It seems clear that the various values of C_n^2 need to be more strongly weighted by their durations than is accomplished by a simple time (or path length) averaging.

We may attempt to approach the problem by using Tatarski's expression for a nonuniform, smoothly varying C_n^2 (and plane wave source):[12]

$$\sigma^2 = 0.56\, k^{7/6} \int_0^L C_n^2(z)\, z^{5/6}\, dz \,, \tag{1}$$

where σ^2 is the log amplitude variance, k is the optical wavenumber, and L is the pathlength. However, rather than a systematic variation of $C_n^2(z)$, i.e. due to a nonuniform path, we have a stochastic variation. Experimentally, C_n^2 varies widely over periods of a few seconds, while σ^2 varies much less. Hence, as stated above, an "effective" C_n^2 should be deducible from the time record of $\Delta T(t)$. Hopefully, such a parameter will readily apply to varying pathlengths and wavelengths, for given statistical variations in C_n^2 (identical average plume situations).

It is therefore tempting to treat σ^2 and C_n^2 as random variables, and to take expectations:

$$<\sigma^2> = 0.56\, k^{7/6} < \int_0^L Cn^2(z)\, z^{5/6}\, dz > \tag{2}$$

However, from a well known theorem in stochastic processes,[13] the order of the expectation and integral operation is interchangeable, and we have simply

$$<\sigma^2> = 0.3\, k^{7/6} <C_n^2>\, L^{11/6} \tag{3}$$

This result (in its point-source form) does not agree with experiment, because the long-time-constant value of C_n^2 — i.e. the true variance of ΔT, including the probability wings in Fig. 7a — is larger than the optically effective value.

One may then treat the problem discretely, utilizing jointly distributed random variables $C_{n_i}^2$ and Δz_j, where the latter are the spatial durations for the ith value of C_n^2. Δz_j may then be related to time durations at a probe installation, using the wind velocity and frozen-in hypothesis. However, as in the continuous case, the final expression contains no appropriate weighting of $C_{n_i}^2$ by its mean duration.

It appears therefore that we require a more fundamental approach to the problem of propagation with a random C_n^2. Due to the quasi-discrete nature of C_n^2 variations in some cases, this solution may be iterative in nature. A further difficulty is that, in the discrete case, if the plume dimension Δz is such that $(\lambda \Delta z < \ell_o^2)$, the value of the inner scale (ℓ_o) also enters. For example, the expression corresponding to Eq. (1) is then[14]

$$\sigma^2 = 7.37\, \ell_o^{-7/3} \int_o^L C_n^2(z)\, z^2\, dz. \tag{4}$$

It is to be hoped that such a theoretical development will be carried out, at least within the Rytov realm, including an extension case of point sources and finite laser sources.

B. Wavelength Dependence of Scintillations

In Fig.10, recent multiwavelength, point-source experimental values of log amplitude variance are shown vs. theoretical values. The "theoretical values" are determined from the short-path 6328Å scintillations and the expression:[15]

$$\sigma^2 = 0.124\, k^{7/6}\, C_n^{\,2}\, L^{11/6} \qquad (5)$$

In all cases, the experimental log amplitude variances were determined from probability slopes and checked against direct analog computer values with an 80 dB system dynamic range.

It is to be noted that, subject to a data spread which relates to the various deficiencies in the atmospheric model and theory under discussion here, the points at 1.15μ and 10.6μ are well clustered about the theoretical line. Also, there is no evidence of 1.15μ or 10.6μ saturation at a lower variance than the typical 0.6 value which is observed at visible wavelengths.[16,17] The reason for the points being below the theoretical line at 4880Å is undoubtedly saturation.

Similar behavior would then have been expected at 1.15μ, but the transmitter at this one wavelength is an approximation to a point source: it constitutes a finite, multimode aperture, and as found in earlier experiments, this tends to increase the variances somewhat. At any rate, many more data points will be obtained over the following months.

Figures 11 and 12 illustrate the fact that $C_n^{\,2}$ values, as obtained from probability slopes and true ΔT variances, result respectively in low and high predictions of scintillations. It is to be noted that the variance at 10.6μ was as high as 0.15, and agreed with the prediction from the 6328Å short-path prediction of $C_n^{\,2}$. This suggests that saturation of 10.6μ scintillations at a level of approximately 0.6 is indeed possible over low paths of the order of 5 km in length.

C. Temperature Structure Function and Turbulence Spectrum

The temperature structure function according to the inertial subrange model is[18]

$$D_T = \langle \Delta T^2 \rangle = C_T^2 \, r^{2/3} \qquad (6)$$

where r is the probe separation, and C_T^2 is defined as the temperature structure constant, which is proportional to the refractive index structure constant. Actual measurements of D_T vs. (r) result in various exponents on r rather than consistent values of (2/3). On log-log paper, the results are generally a straight line to an outer scale of roughly 25% of the height of the probes, but the slope at mid-day is more generally near 0.5 and has been observed to be as small as 0.3.

Typical results for $\langle \Delta T^2 \rangle$ with 100 second time constants and 5 minute averaging times, are shown in Figs. 13 and 14. In Fig. 14, the variance as determined from the probability slope at the center of the ΔT distribution, is shown in addition to the true variance. These points do not comprise as good a straight line, but the slope is more nearly equal to the theoretical value. This may indicate that the inertial subrange applies outside of the high-turbulence plumes.

The rms spectrum of single-probe temperature fluctuations is predicted within the inertial subrange model[18] to fall-off as $\omega^{-5/6}$. This is the so-called "5/3" law, referring to the mean-square values. Again, the actual values usually fall-off with a constant exponent or as a straight line on log-log paper, but with various slopes.

Midday results for five different days are shown in Figs. 15a-e. In all cases, the spectral points are taken from a "common time window", i.e.

a five minute recording of ΔT on magnetic tape, using a 100 second time constant. The spectrum analyzer is a Quantech Model 304 unit, utilizing a 1 Hz bandwidth. In all but one case, the magnitudes of the slopes are less than the theoretical value of 0.833. The response of the system extends well below 1 Hz, and at the low-frequency end, the outer scale is apparently manifested by a departure in either direction from a straight line. At the high-frequency end, the inner scale is manifested in Figs. 15a-c by break-points,(19) which correspond to days of unsteady, low wind. The high-frequency data are corrected for system noise and probe response, and the values of the outer and inner scales are inferred from the spectra and mean wind velocities.

Lawrence(8) interprets the departure from the ideal exponents as a manifestation of continuing energy fed in at respectively smaller scales within the supposed inertial subrange. The probe-separation and spectral data contain the same information, except that the spectral method is more suitable for inner scale determinations and hence for predicting optical effects.

It is seen that the spectrum of temperature fluctuations constitutes a convenient and powerful means of examining the turbulence spectral exponent and inner scale size. The midday values of these parameters are highly variable according to weather conditions, and it is known that variations are even more pronounced over diurnal cycles, which include neutral and inversion conditions.(8,17) It should be mentioned that the turbulence structure may also be explored with very-short-path optical techniques, utilizing the covariance of scintillations.(20,21)

It is worth noting that the departure of the turbulence spectrum from the inertial subrange characteristic constitutes no fundamental new problem in deriving the expected (Rytov) scintillations, and C_n^2 may still be defined without difficulty.(18) The dependence of scintillations on wavelength and pathlength will vary with the spectral characteristic. It has been pointed out[22] that if the Kolmogorov spectrum is to be used as an approximation, then the probe separation employed in deducing C_n^2 should be small, since this corresponds with scale sizes important in the optical filter function.[3]

D. C_n^2 vs. Height and Probe Direction

The approximate beam height in these experiments is two meters. At points this near the ground, the value of C_n^2 varies significantly with height, as shown in Fig. 16.

Measurements were also made of C_n^2 or $< \Delta T^2 >$ with various orientations of the probe-separation vector relative to the wind direction. No systematic variation was found.

III. PLANS FOR PHASE III

Utilizing the recently developed techniques for examining the turbulence structure independent of optical effects, a final "standard run" procedure has evolved in which the following measurements are made:

1. Probability and spectral distribution of ΔT for a five minute "time window", which gives the turbulence spectrum and approximate inner scale.

2. C_n^2 as deduced from #1 above, from $< \Delta T^2 >$, and from the short-path 6328Å laser.

3. Simultaneous log amplitude variances/covariances at 4880Å, 1.15μ, and 10.6μ, for the total path.

4. Simultaneous probability distributions of the log amplitude scintillations at the above three wavelengths.

5. Simultaneous scintillation spectra at the three wavelengths.

6. Aperture-averaging at 4880Å (and possibly other wavelengths).

7. Pertinent meteorological parameters.

These standard runs are underway and will be repeated a number of times under normal lapse conditions, for both saturated and unsaturated visible-wavelength scintillations. They will then be repeated over diurnal cycles, in order to relate the scintillations to the inner scale and turbulence spectrum for neutral and inverted conditions.

Following the completion of this, the effects of finite transmitter apertures will be examined. Further experiments will then be chosen from the following possibilities:

1. The ΔT probability slope vs. probe separation, to determine if the Kolmogorov spectrum tends to hold outside of plumes.

2. Careful analysis of log scintillation probability tails, in order to compare the accuracy of log normal vs alternative distributions.

3. Scintillation statistics at beam edges.

4. Longer-path variances and covariances.

IV. PRESENTATIONS AND PAPERS

During the period covered by this report, a number of presentations have been given to government agencies, and certain portions of the instrumentation are being duplicated and utilized by Department of Defense and NASA investigators. Two oral papers[23, 24] and a detailed discussion[25] have been given at Optical Society of America meetings, and a written paper will be submitted for publication in the near future. A related paper on optical communications through the atmosphere will be published in September, 1970.[26]

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FIGURES

1. Temperature fluctuations vs. time. Horizontal scale: 10 seconds per division. Vertical scale: 0.36°C per division. Date: May 14, 1970. Wind: unsteady, 0-5 mph. Weather: clear.

    a. Single probe
    b. Double probe (temperature-difference)

2. Temperature fluctuations vs. time. Horizontal scale: 10 seconds per division. Date: June 23, 1970. Wind: steady, 10 mph. Weather: clear.

    a. Single probe, 1.78°C per division.
    b. Double probe, 0.36°C per division.

3. Temperature-difference (2 probes) vs. time. Horizontal scale: 10 seconds per division. Vertical scale: 0.36°C per division. Date: May 15, 1970. Wind: unsteady, 0-2.5 mph. Weather: clear.

4. C_n^2 vs. time. Horizontal scale: 10 seconds per division. Vertical scale: $1.1 \times 10^{-12} m^{-2/3}$ per division. Date: May 14, 1970. Wind: unsteady, 0-5 mph. Weather: clear.

5. Temperature-difference (2 probes) and wind speed vs. time. Horizontal scale: 10 seconds per division. Vertical scale: 0.36°C per division and 1.8 mph per division. Date: May 14, 1970. Weather: clear. Note: minor oscillations in wind speed signal are instrumental.

6. Spectral components of temperature fluctuations in 1 Hz passband, centered at 2 Hz and 100 Hz, vs. time. Horizontal scale: 10 seconds per division. Date: May 26, 1970. Wind: unsteady, 0-8 mph. Weather: cloudy.

7. Probability distributions of temperature-difference fluctuations (2 probes). Date: June 23, 1970. Wind: steady, 10 mph. Weather: clear.

    a. Discrete points taken with 5 minute averaging time, each on the same (recorded) time period.

    b. Real-time sweep taken in approximately one minute each.

8. C_n^2 as deduced from probability slope vs. that from temperature variance.

9. C_n^2 as deduced from probability slope vs. that inferred from short-path laser scintillations.

10. Theoretical vs. experimental log amplitude variance. The theoretical value is taken from C_n^2 as inferred from the short-path scintillations.

    a. 4880 Å
    b. 1.15 microns
    c. 10.6 microns

11. Theoretical vs. experimental log amplitude variance. The theoretical value is taken from C_n^2 as inferred from probability slopes of temperature-difference fluctuations. Wavelengths as above.

12. Theoretical vs. experimental log amplitude variance. The theoretical value is taken from C_n^2 as inferred from the true variance of temperature-difference fluctuations. Wavelengths as above.

13. D_T vs. probe separation (r). D_T is obtained from the true temperature-difference variance averaged over five minutes. Date: June 4, 1970. Wind: steady, 10 mph Weather: clear.

14. D_T vs. probe separation (r). D_T is obtained from the true temperature-difference variance, and from the probability slope of temperature-difference fluctuations. Date: June 12, 1970. Wind: unsteady, 6-15 mph. Weather: clear.

15. Spectra of single-probe temperature fluctuations. Inner and outer scales are deduced from spectral breakpoints and mean wind speeds. Discrete points are taken with 5 minute averaging time, each on the same (recorded) time period.

    a. May 21, 1970. Wind: unsteady, 0-4 mph. Clear.
    b. May 26, 1970. Wind: unsteady, 0-8 mph. Cloudy.
    c. May 28, 1970. Wind: very unsteady, 0-5 mph. Clear.
    d. June 1, 1970. Wind: steady, 3.5 mph. Clear.
    e. June 23, 1970. Wind: steady, 10 mph. Clear.

16. C_n^2 vs. height (h). C_n^2 is obtained from true temperature-difference variance. Date: June 4, 1970. Wind: steady, 10 mph. Clear.

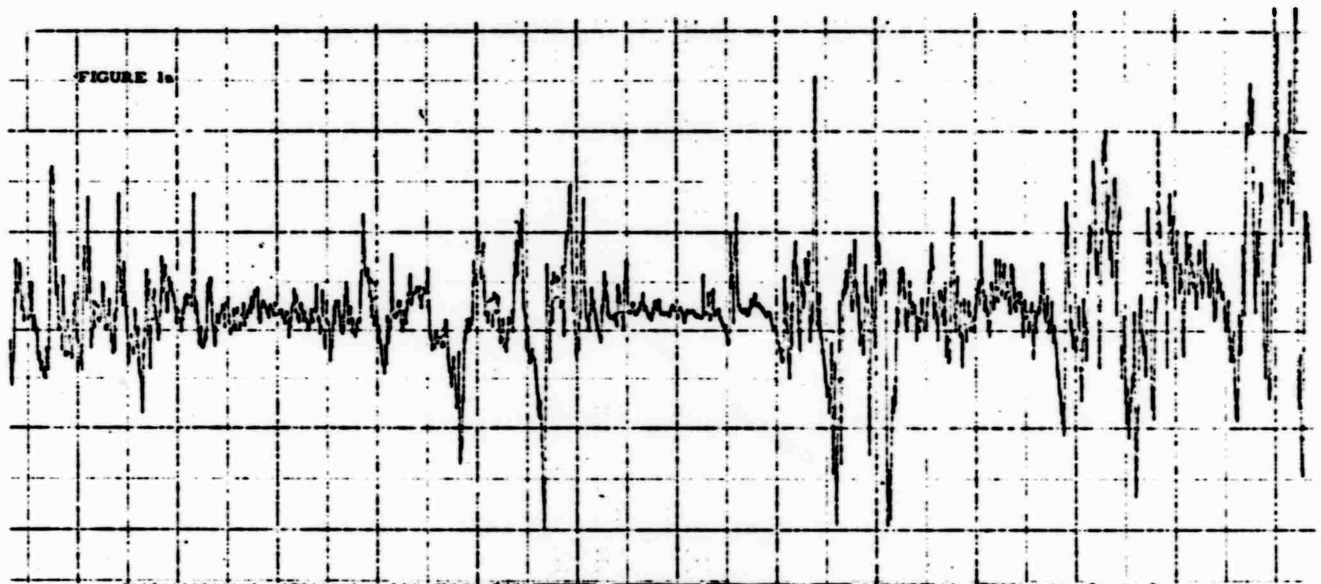


FIGURE 1a

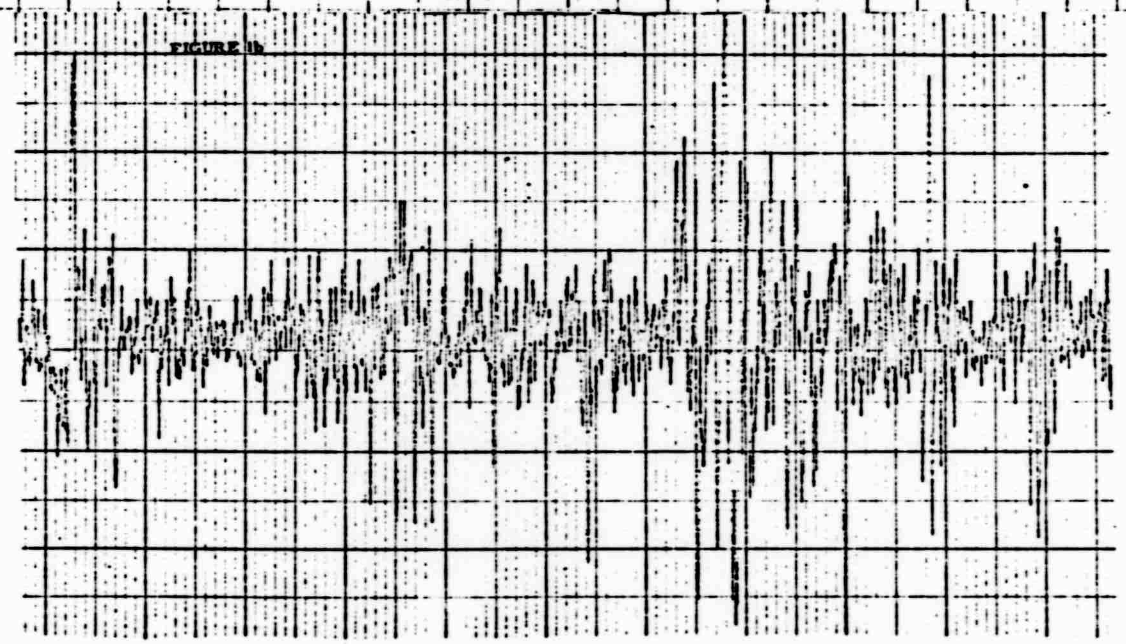
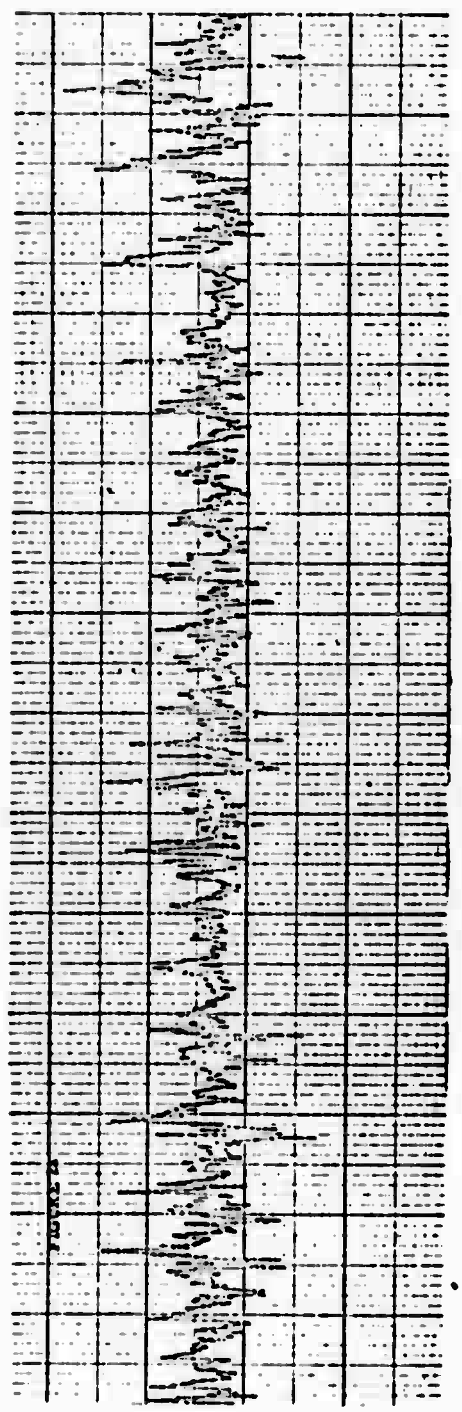


FIGURE 1b



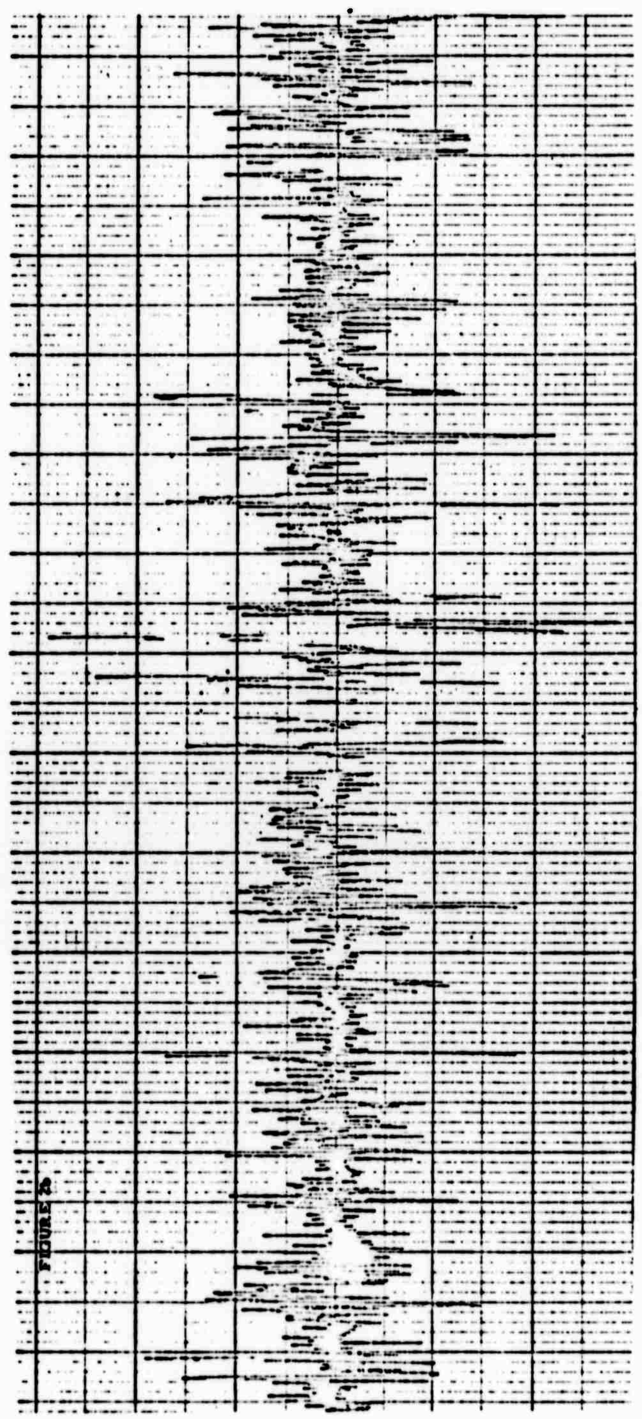


FIGURE 2

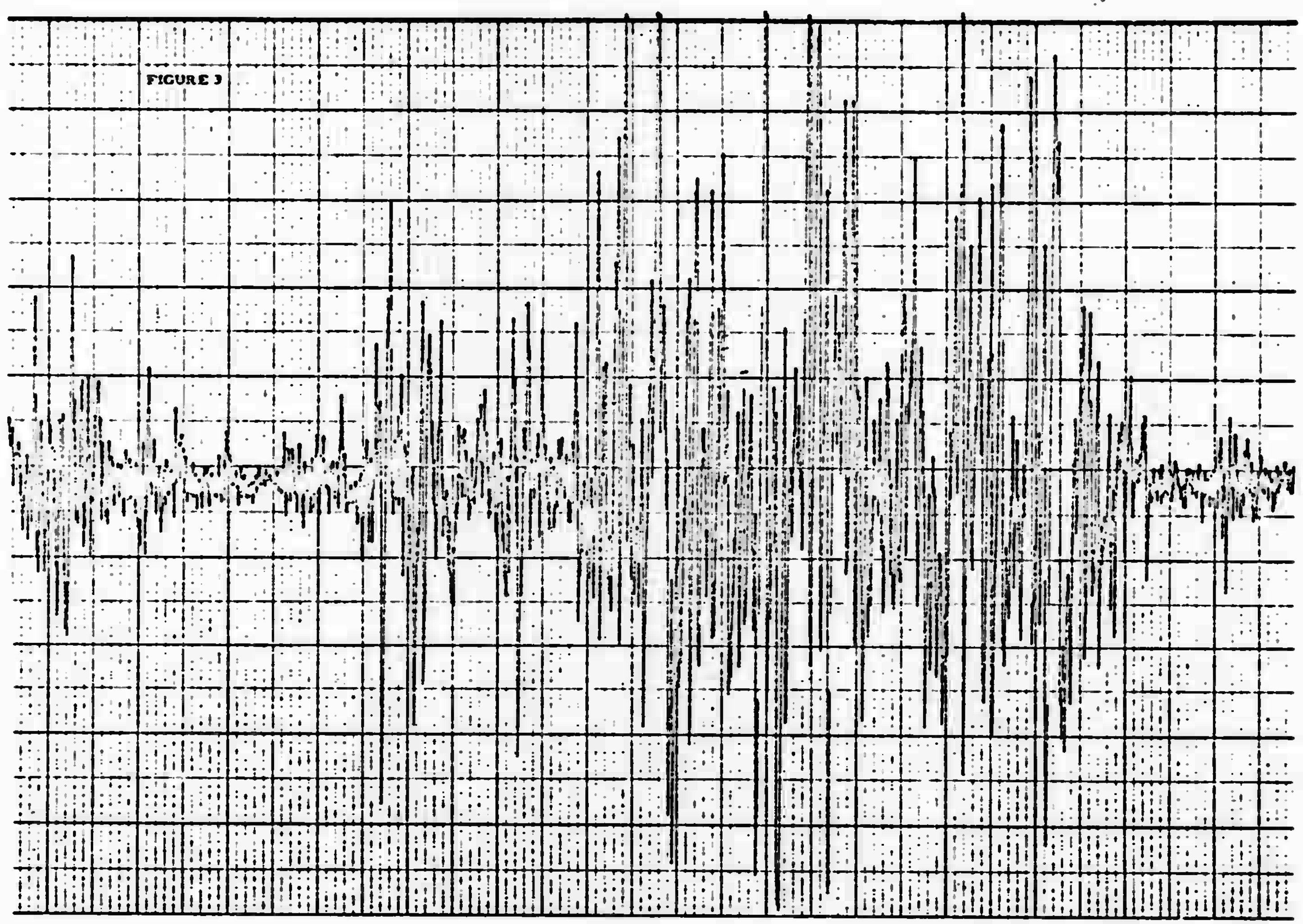


FIGURE 3

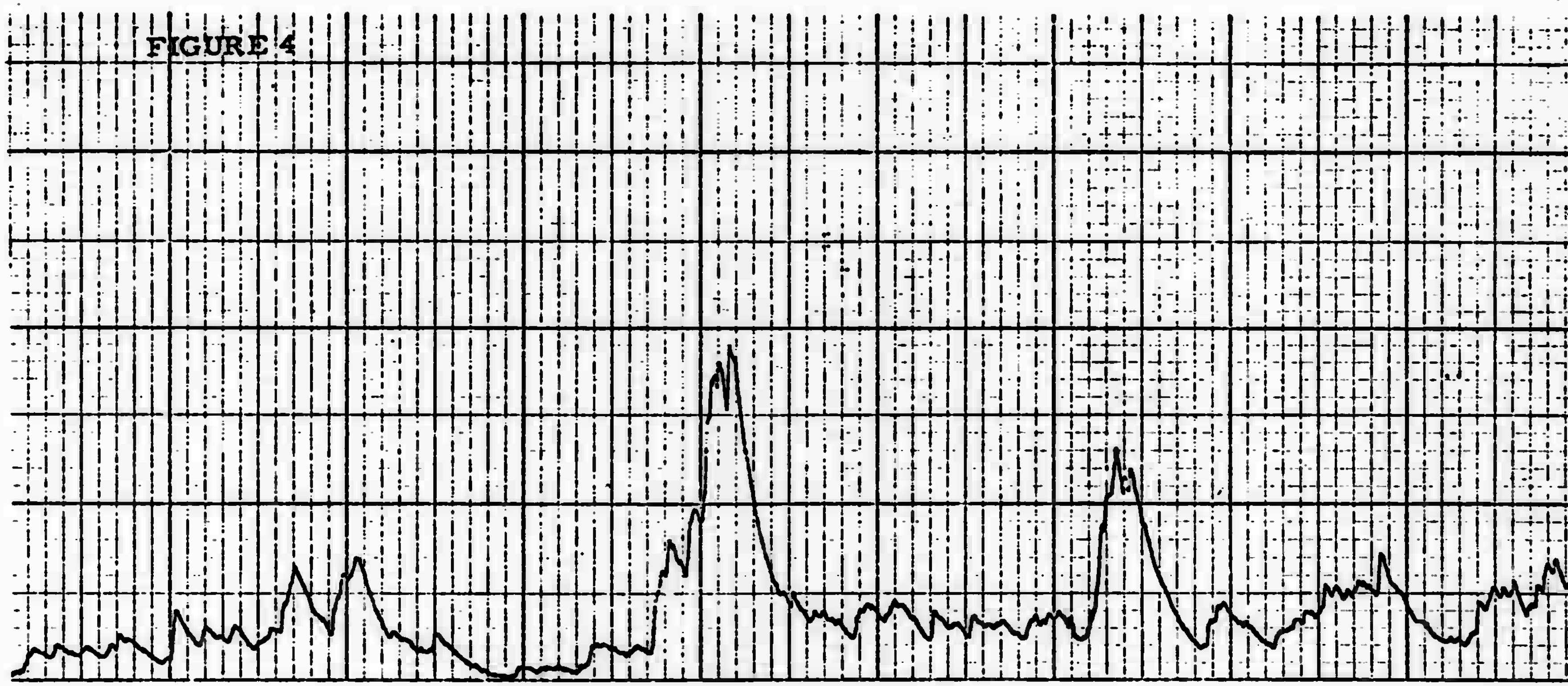


FIGURE 4

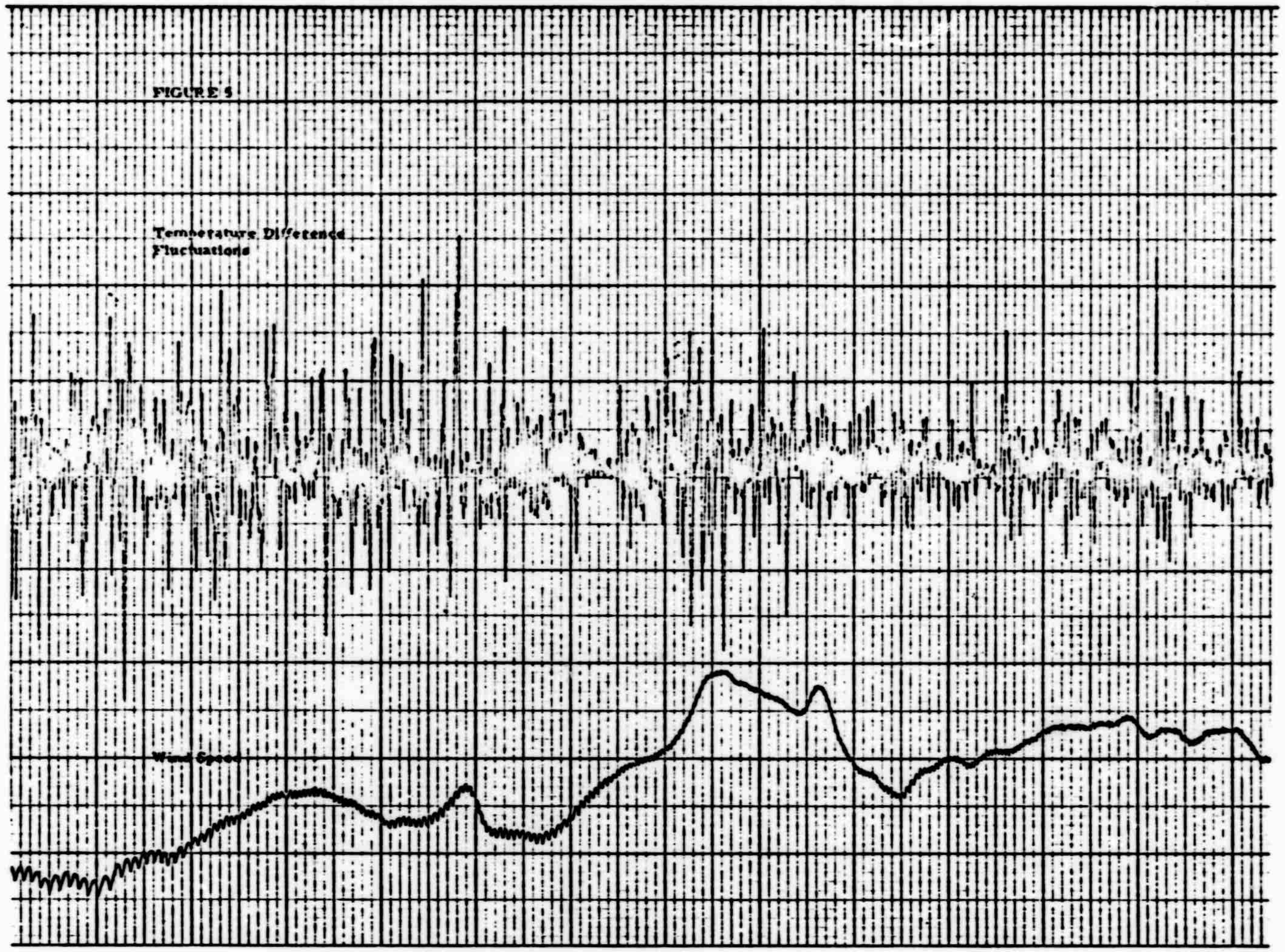


FIGURE 5
Temperature Difference
Fluctuations
Wind Speed

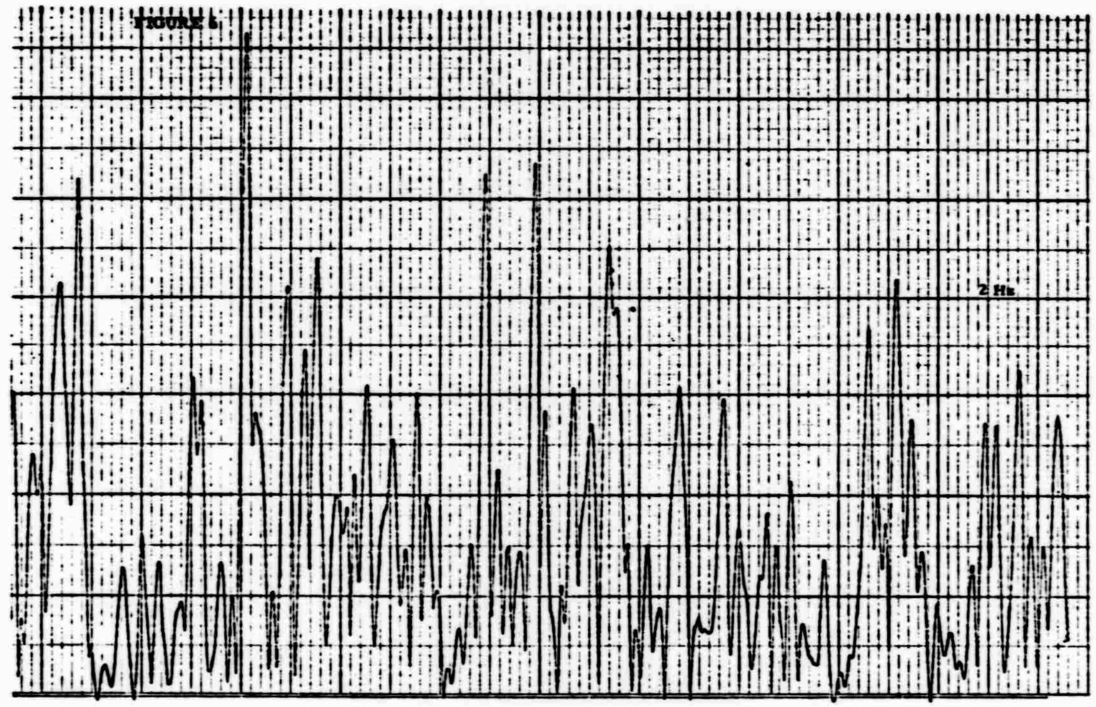
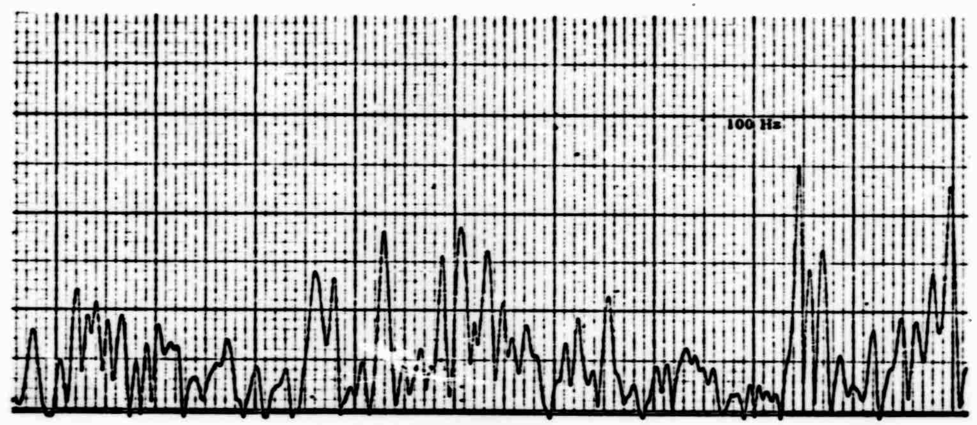


FIGURE 6


100 Hz

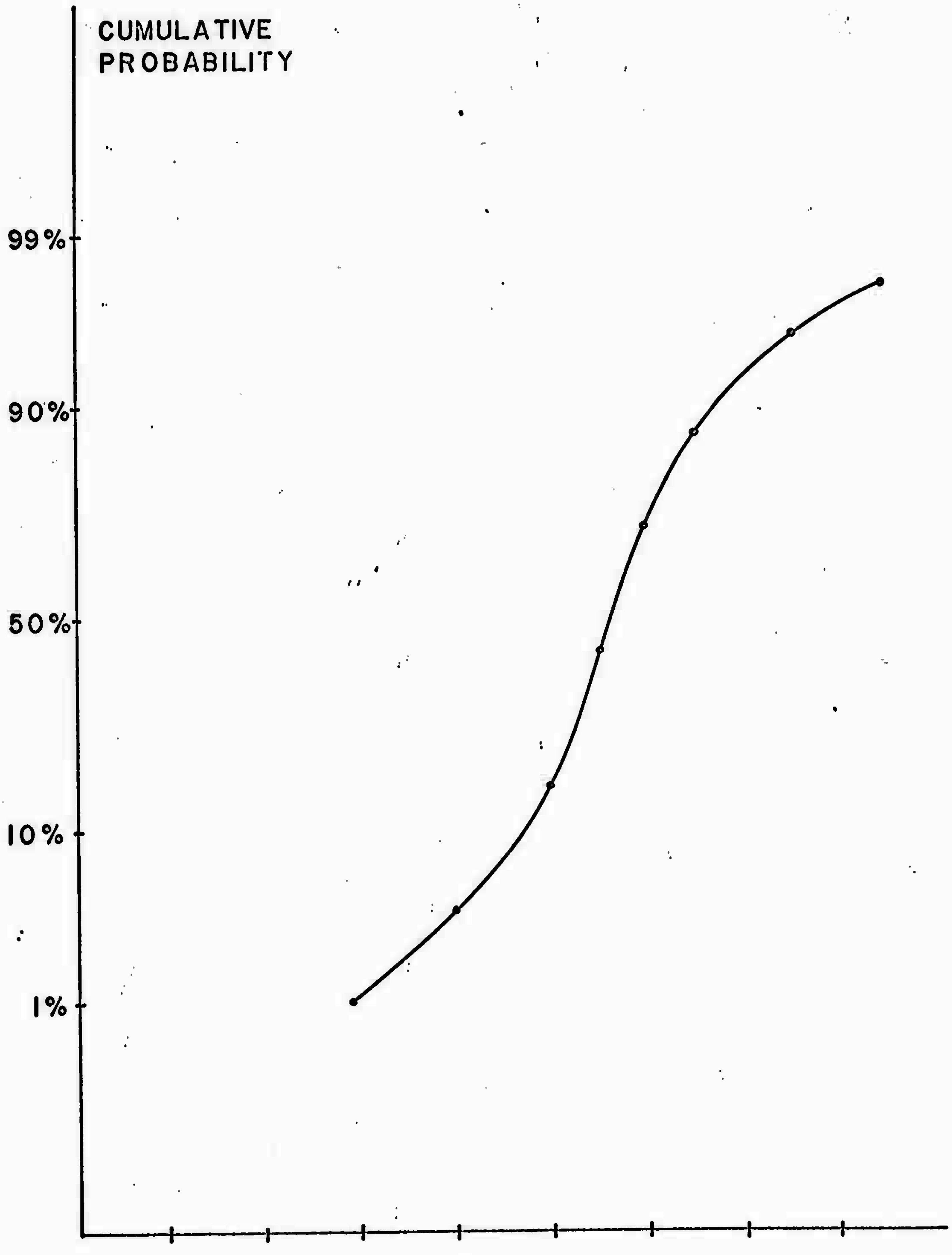


Figure 7a

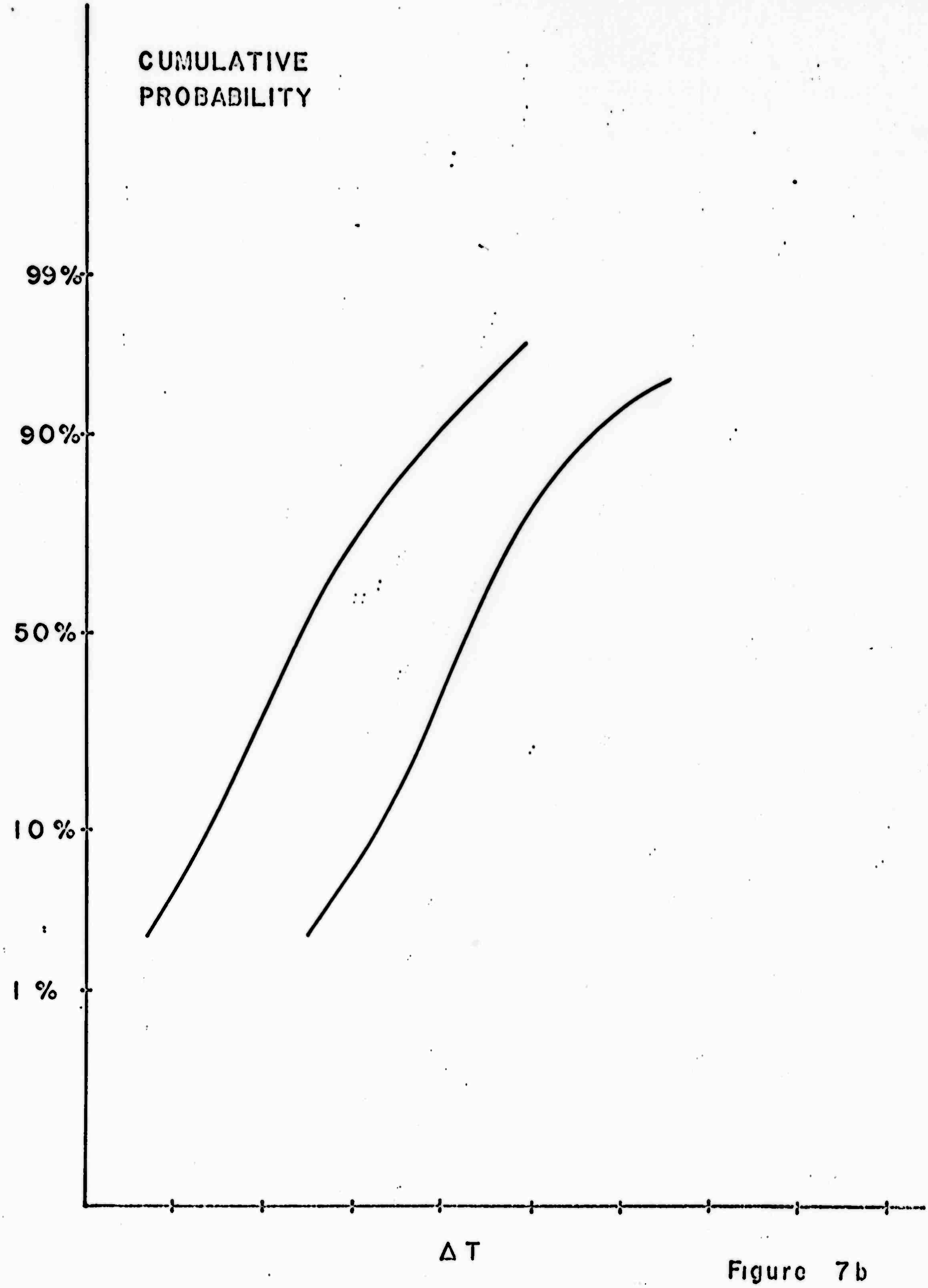
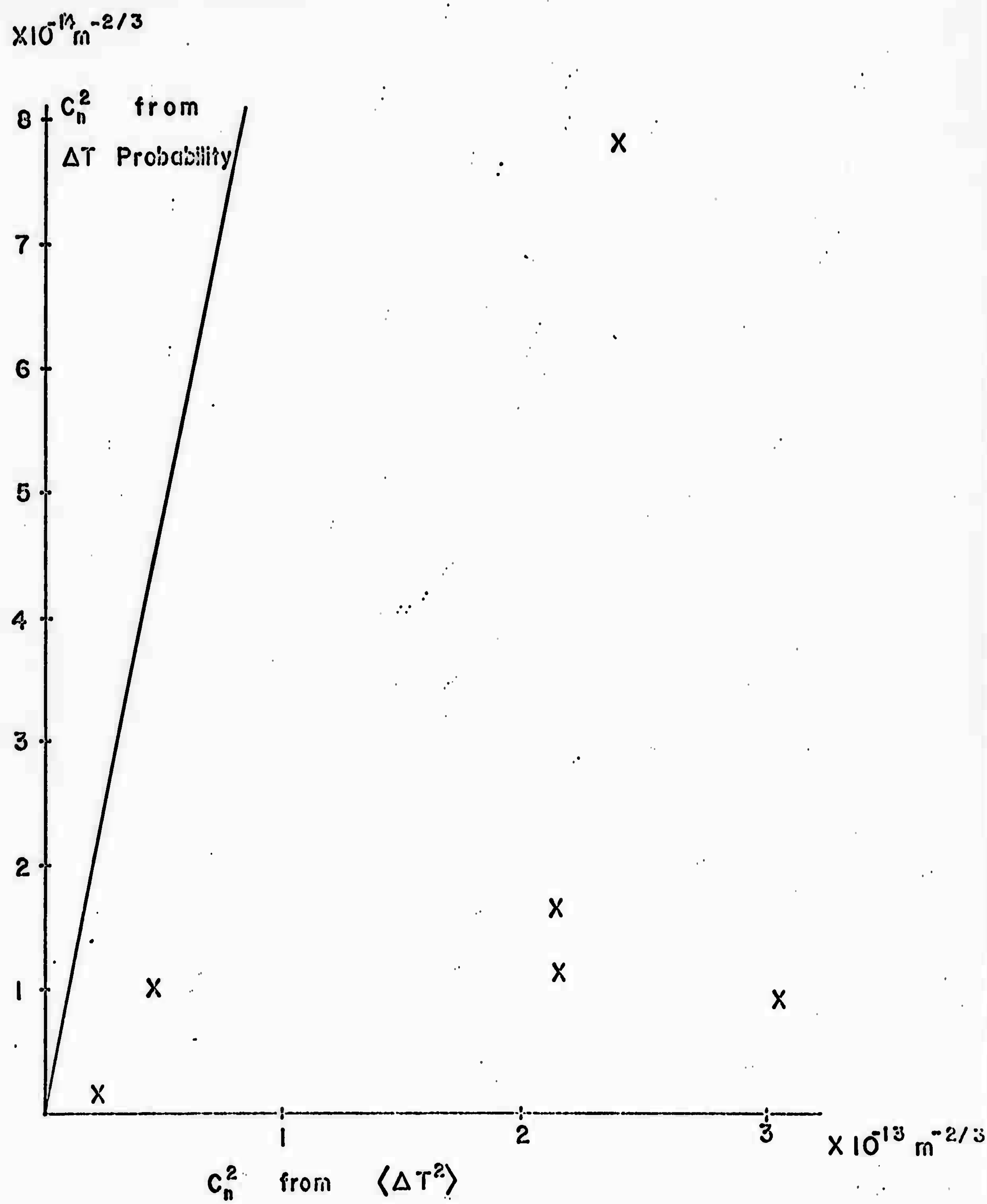
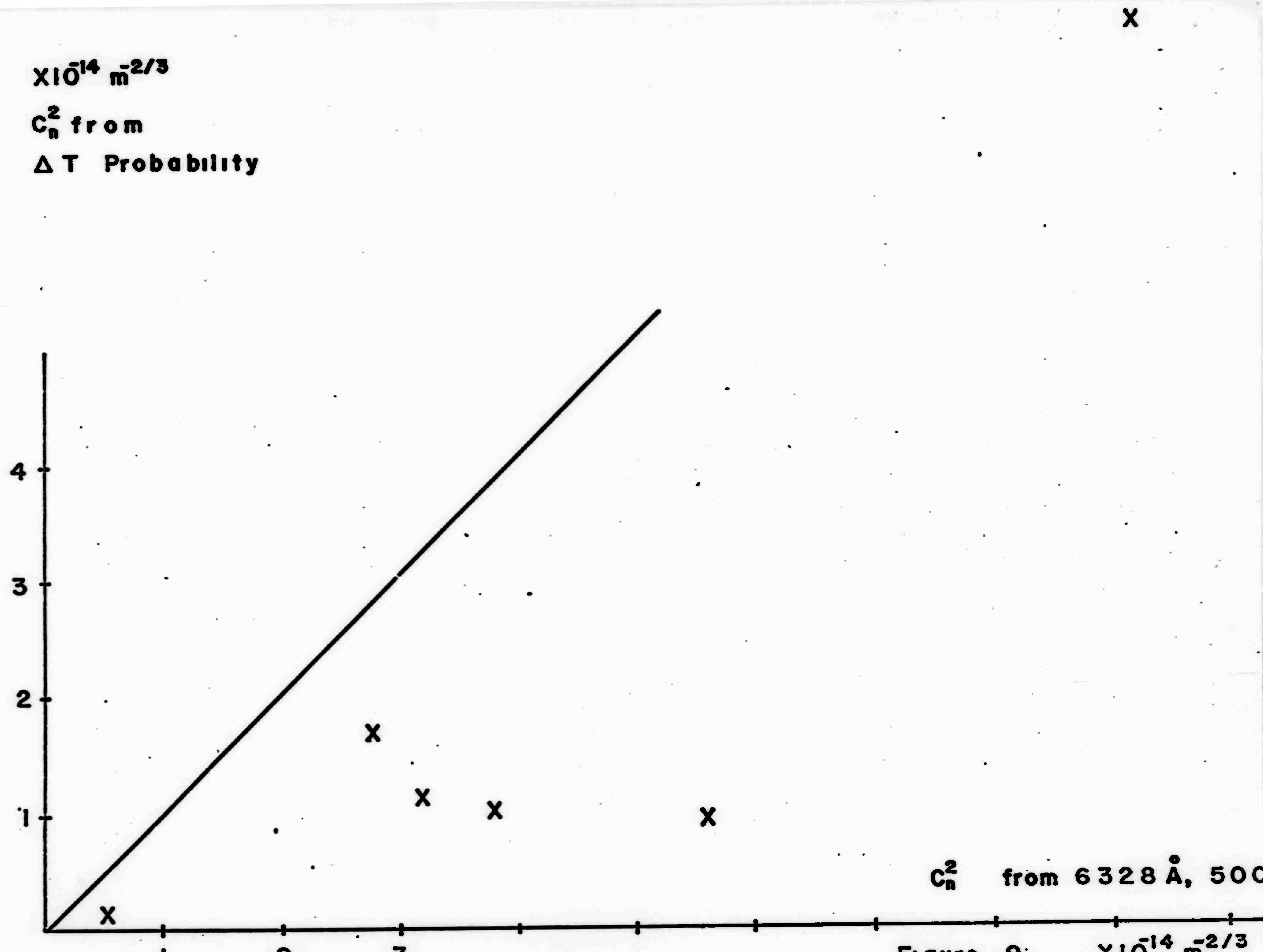


Figure 7b



X10^{-14}m$^{-2/3}$
C_n^2 from
ΔT Probability
8
7
6
5
4
3
2
1
1
2
3
X 10^{-13} m$^{-2/3}$
C_n^2 from ⟨ΔT^2⟩

Figure 8



X10^{-14} m$^{-2/3}$
C_n^2 from
ΔT Probability
4
3
2
1
1
2
3
C_n^2 from 6328 Å, 50C
X10^{-14} m$^{-2/3}$

Figure 9

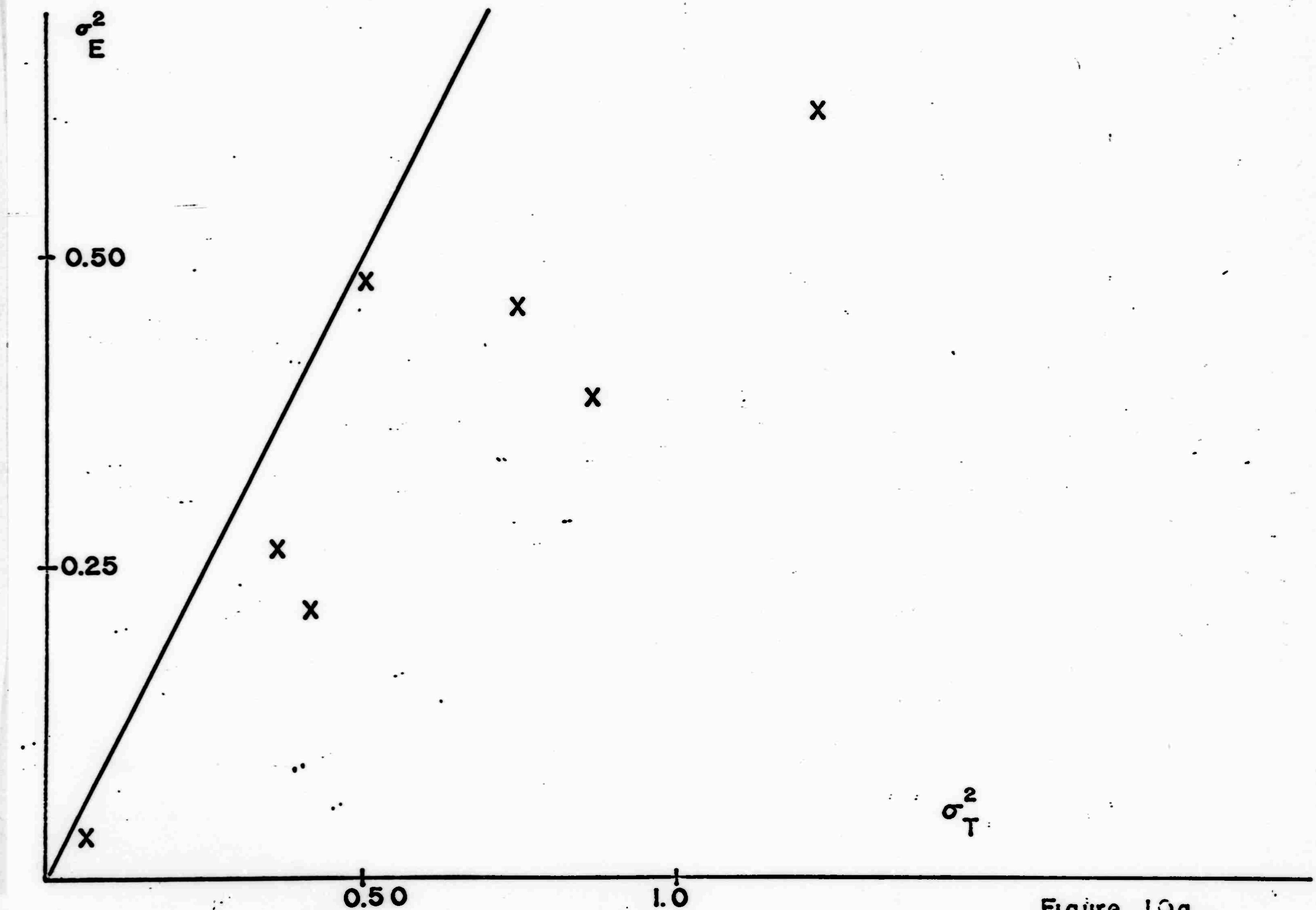


Figure 10a

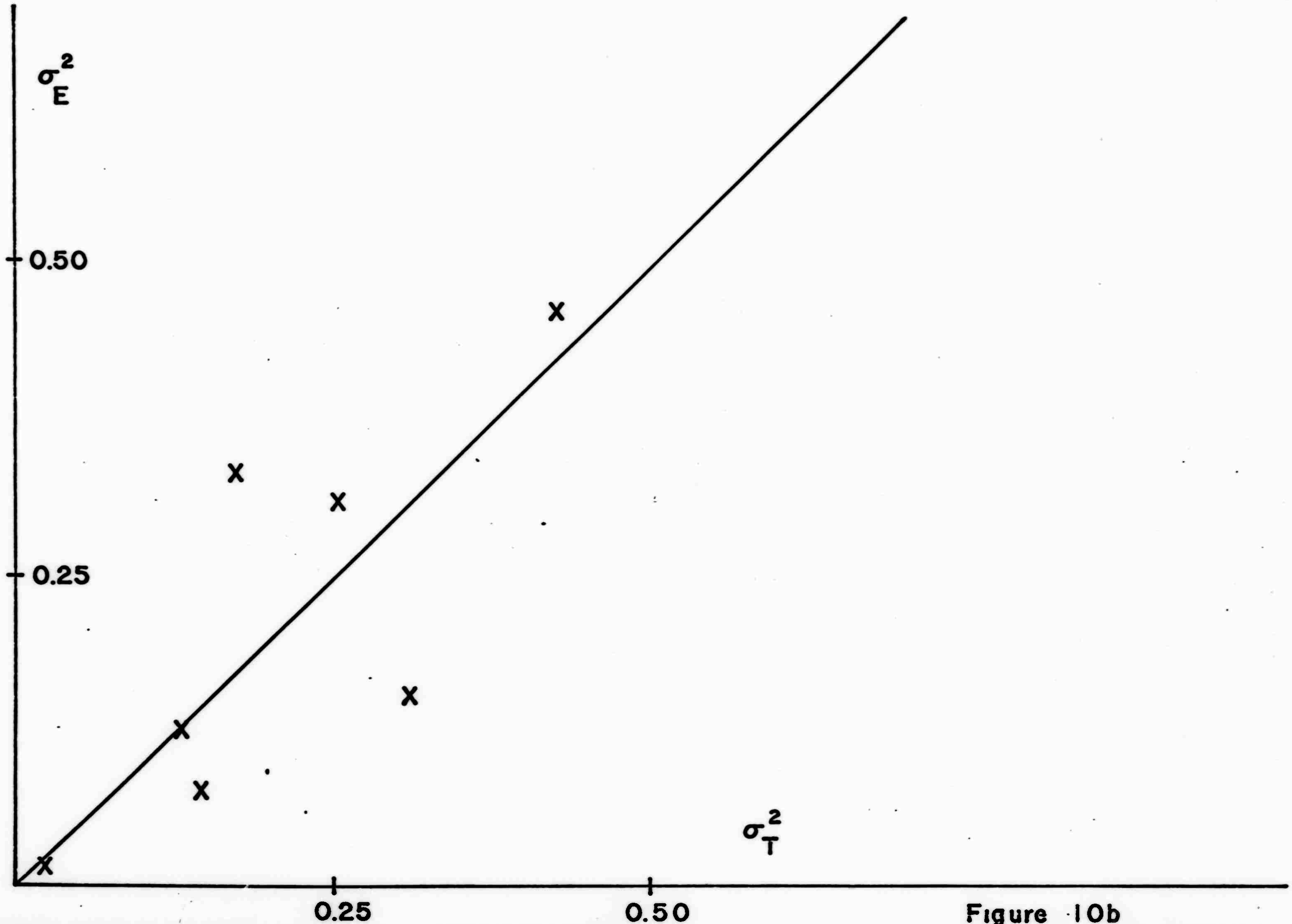


Figure 10b

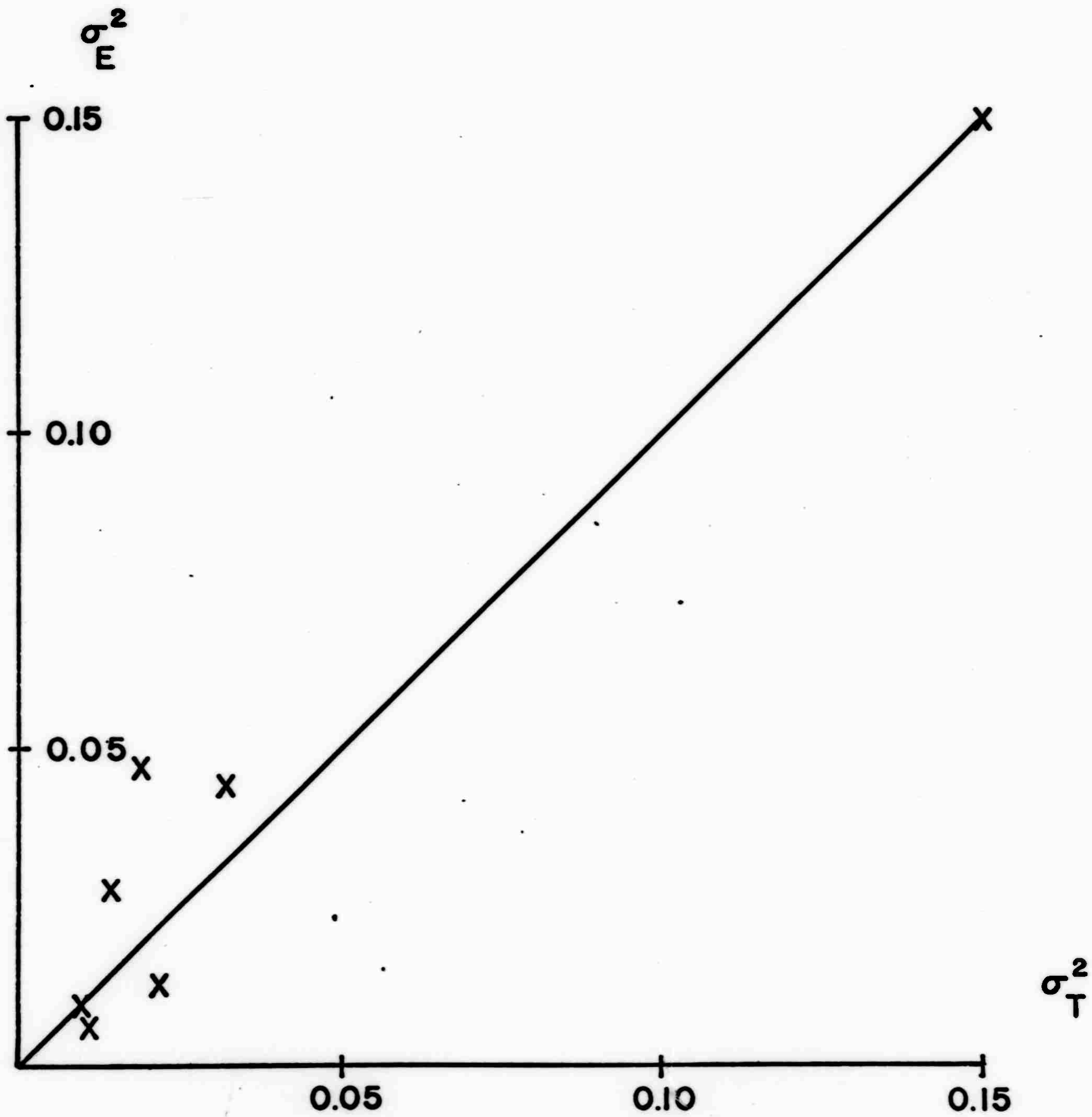


Figure 10 c

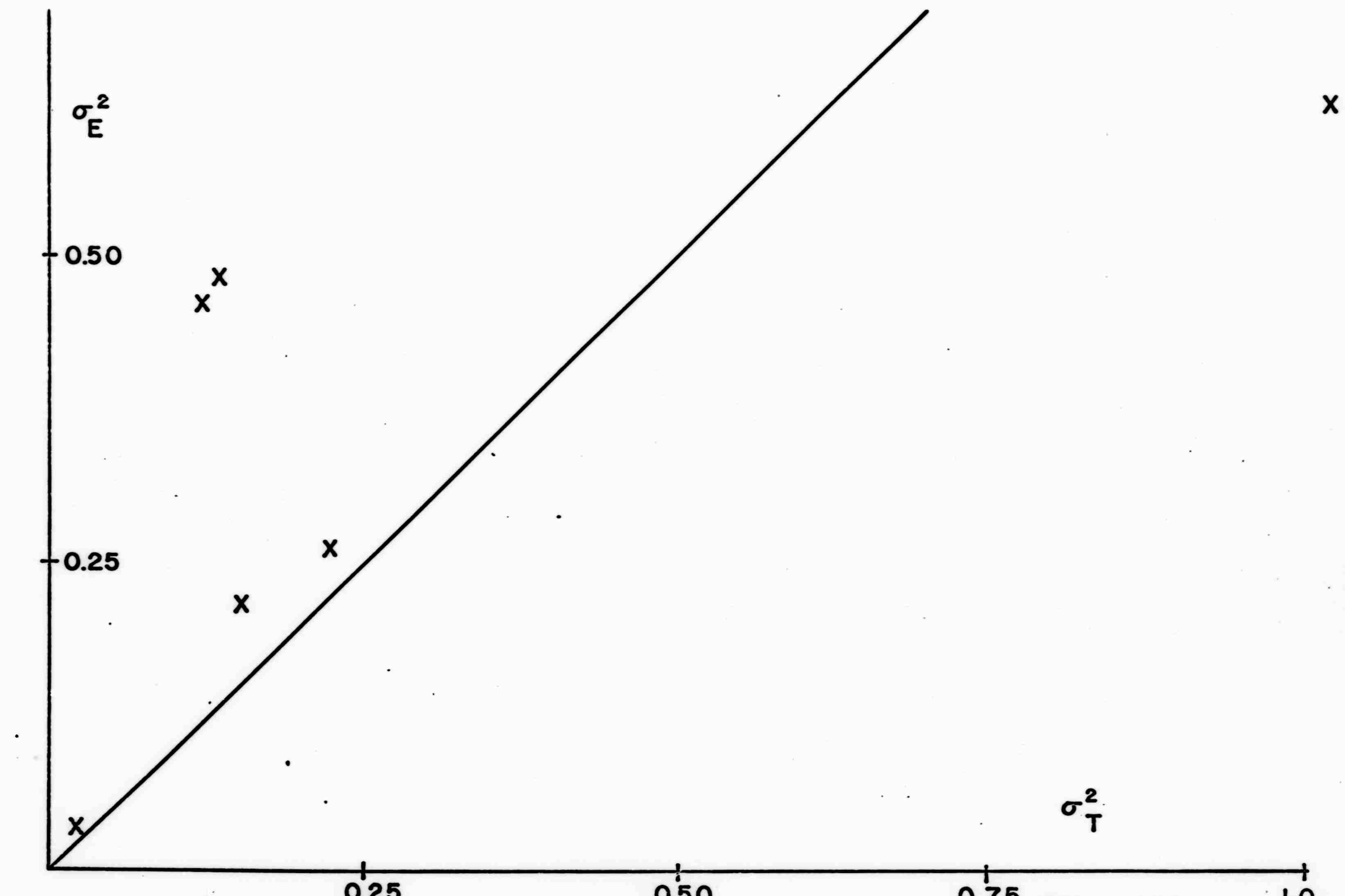


Figure 11a

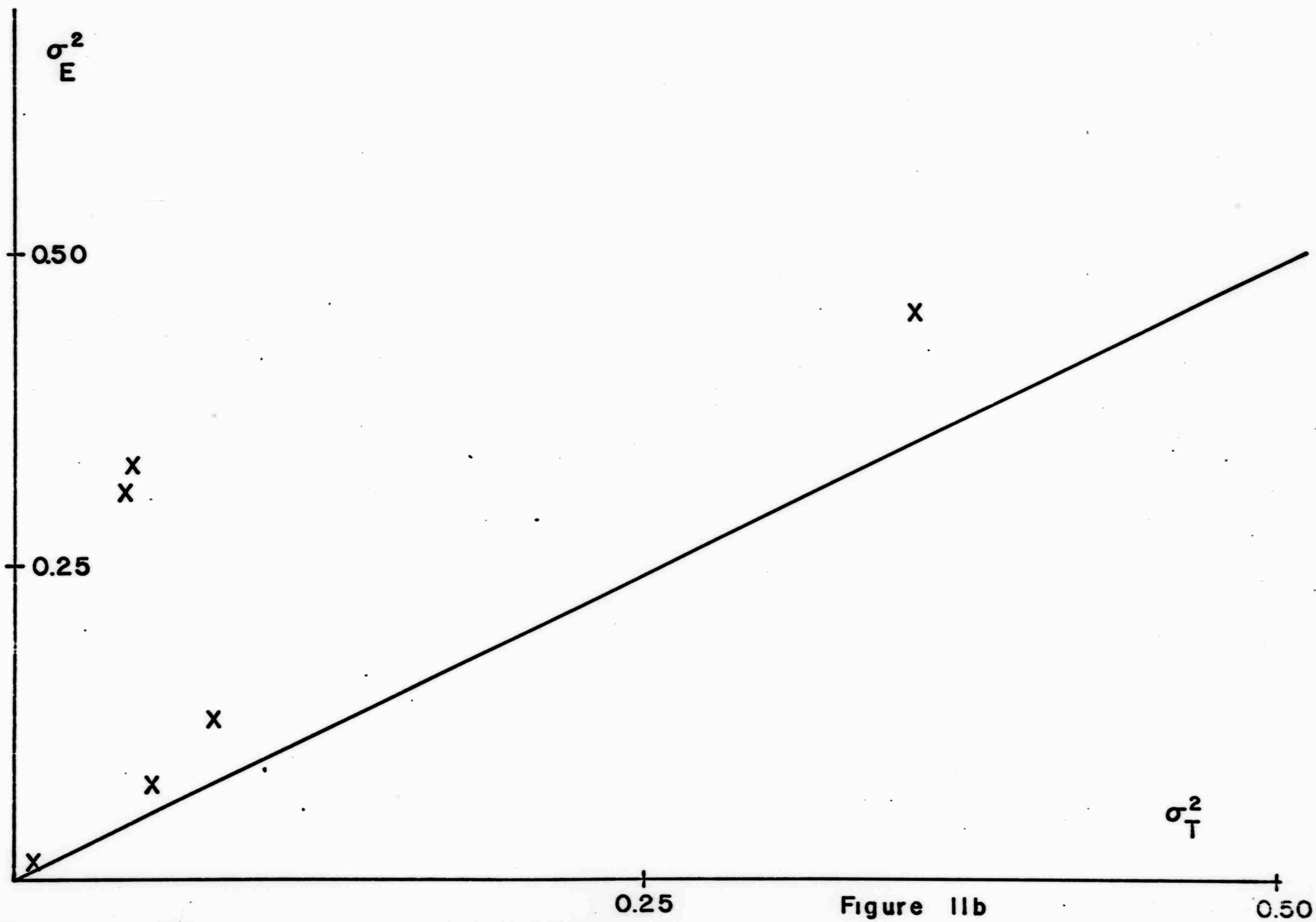


Figure 11b

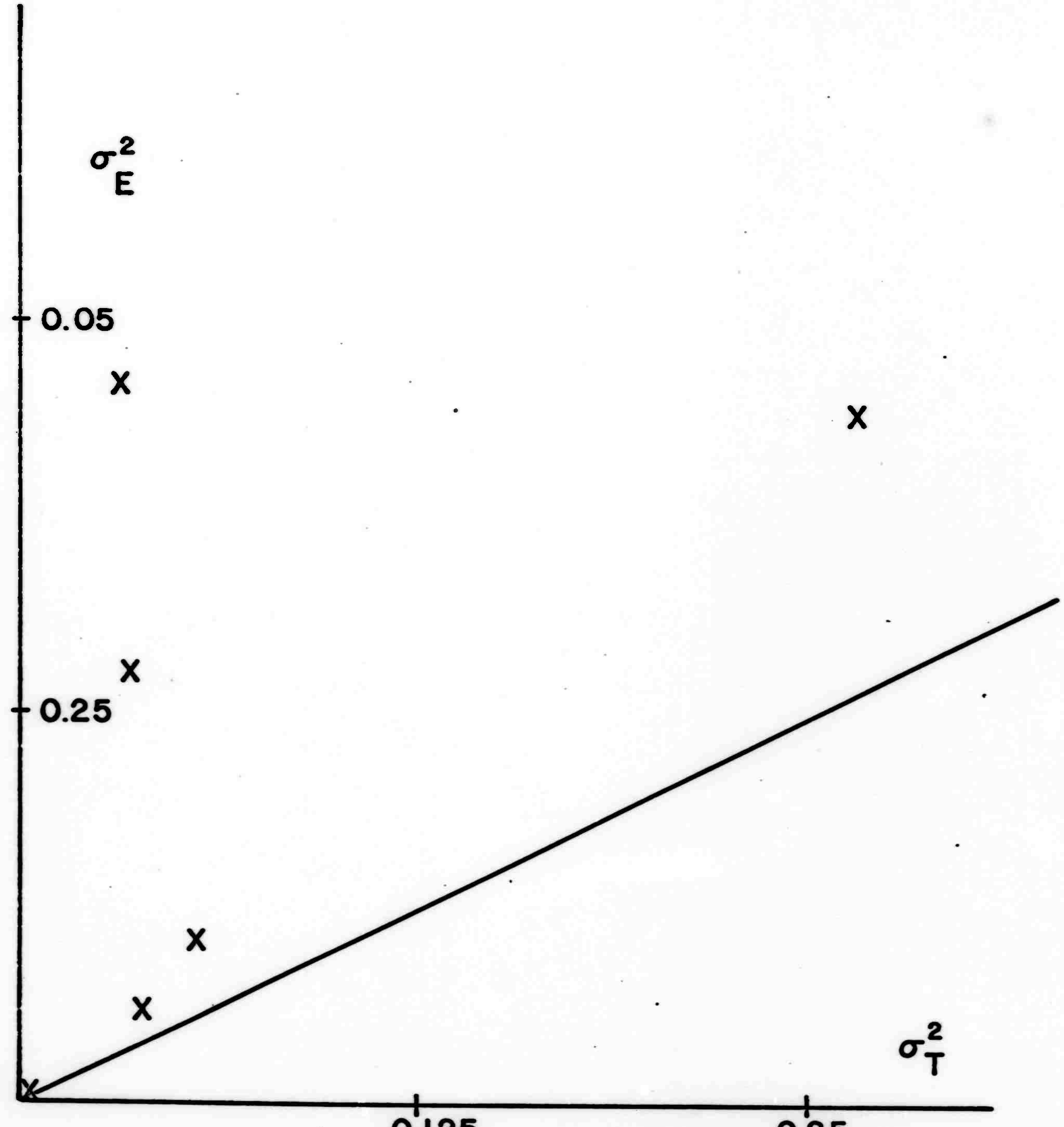


Figure 11c

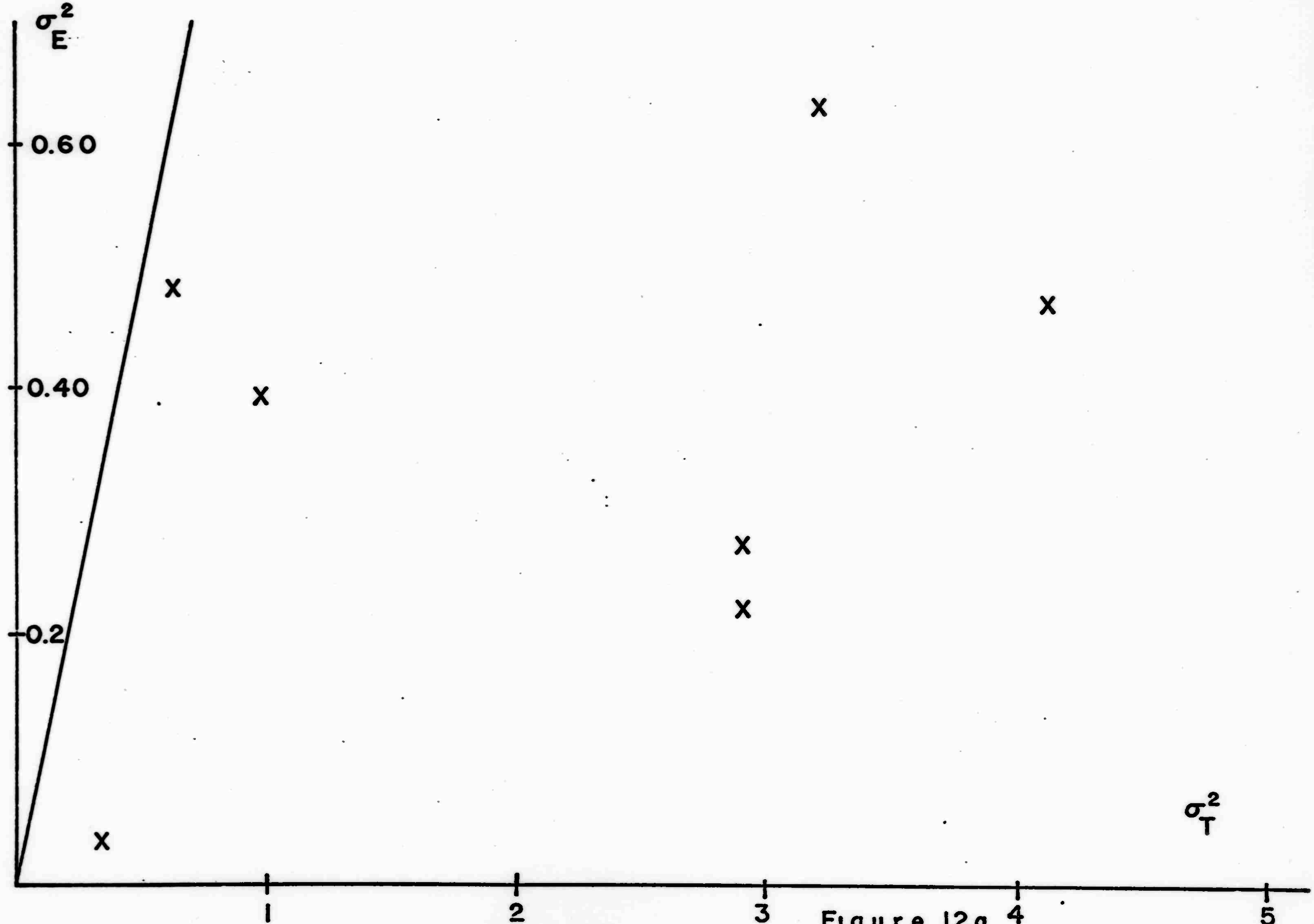


Figure 12a

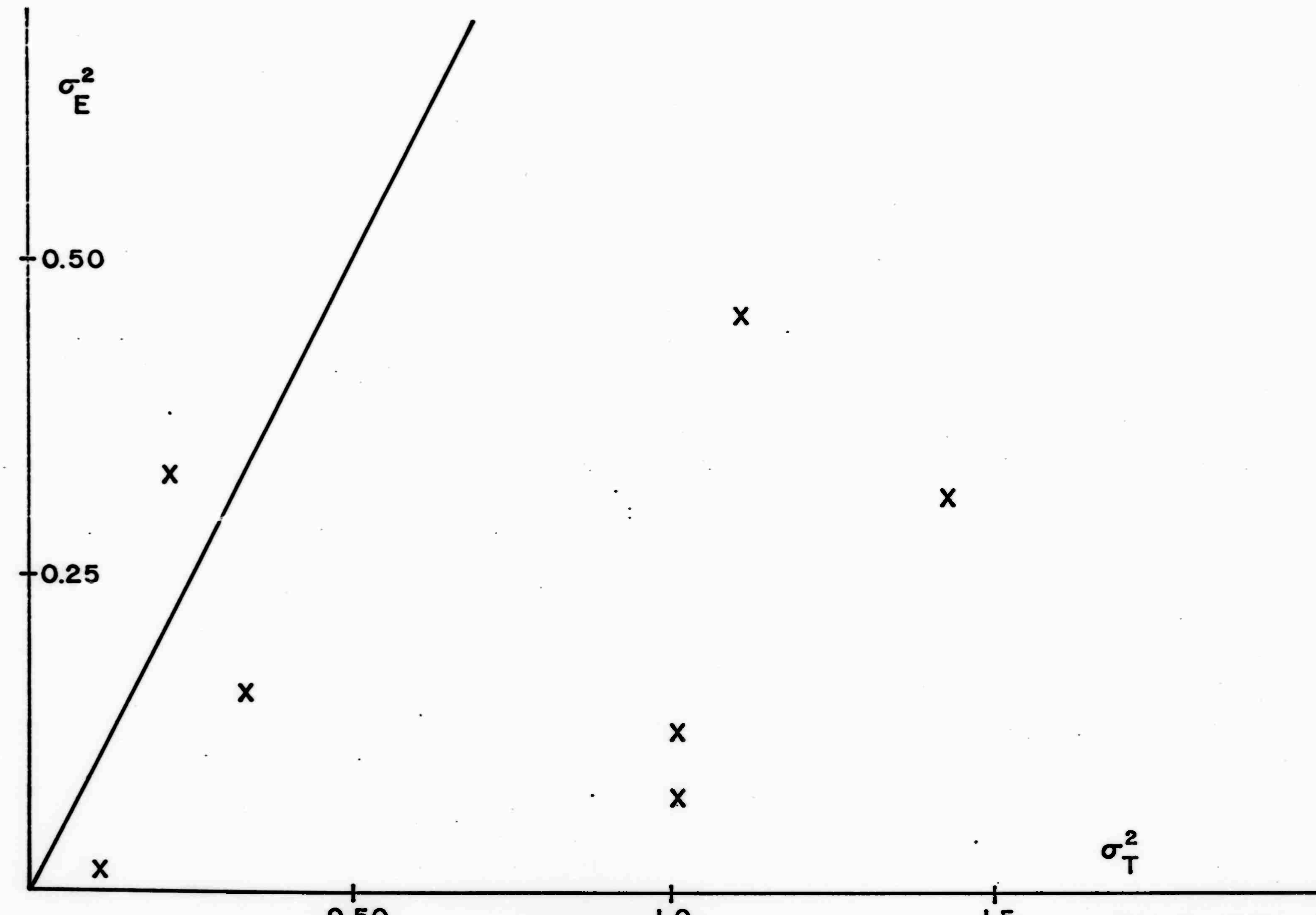


Figure 12b

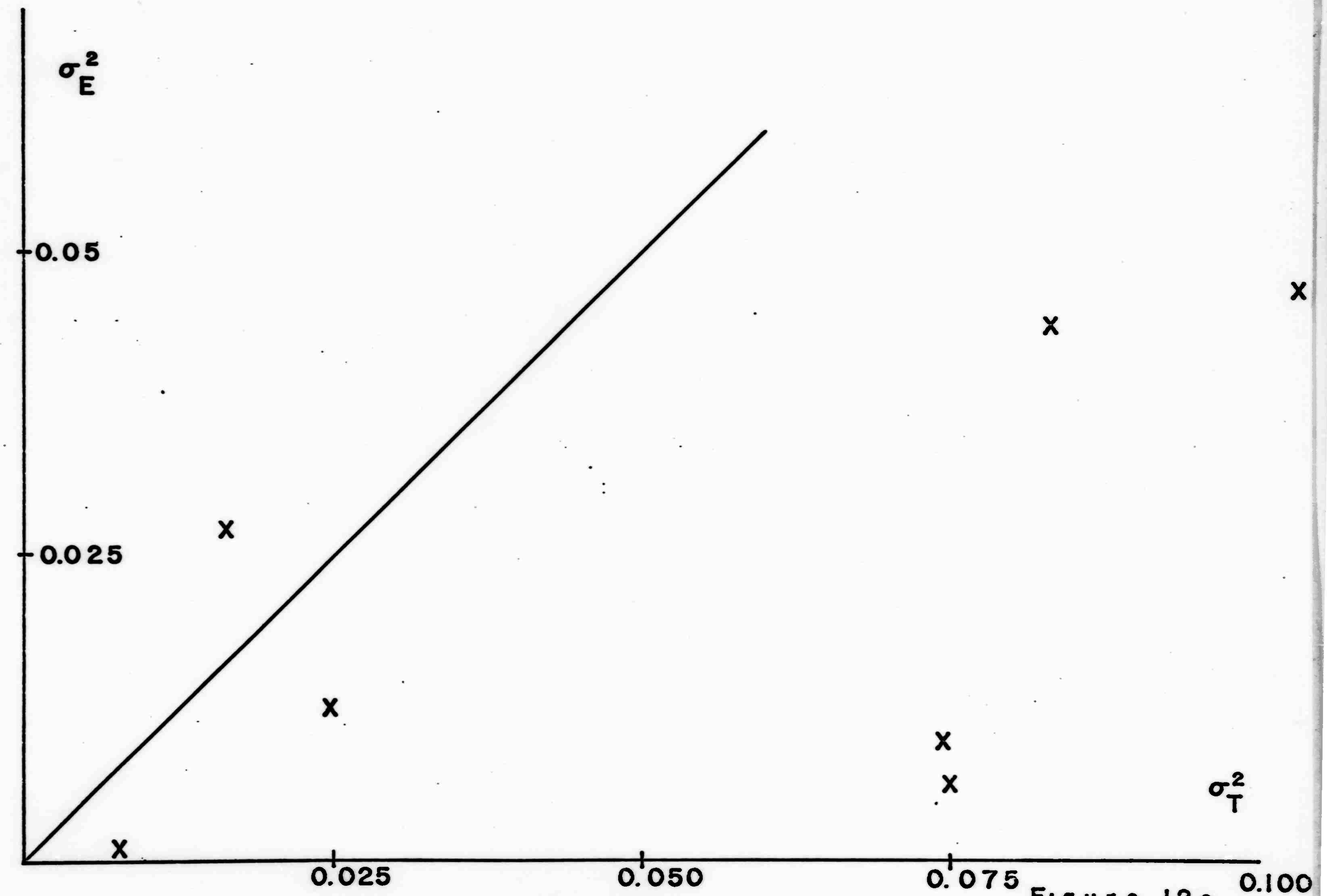


Figure 12c

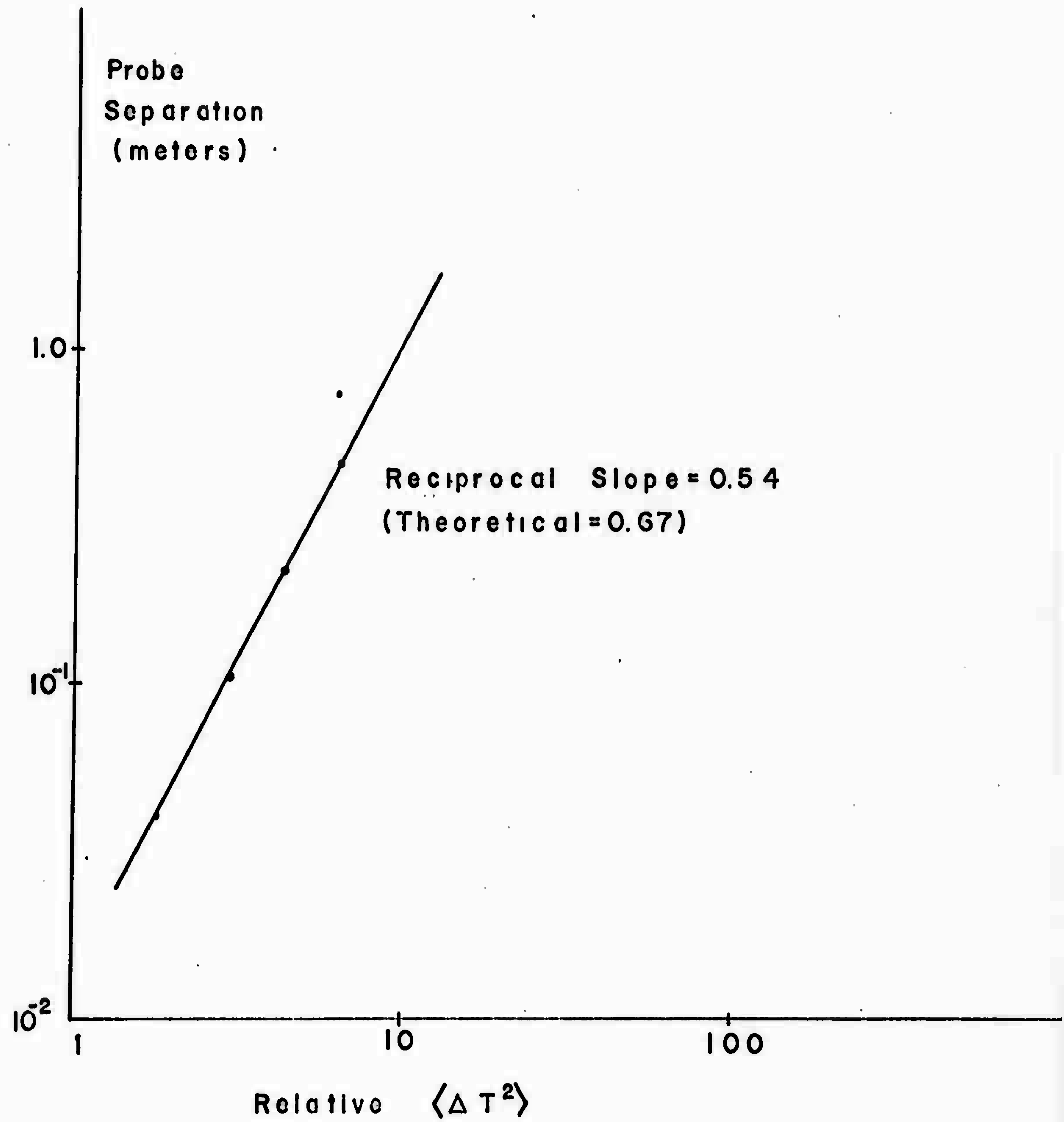
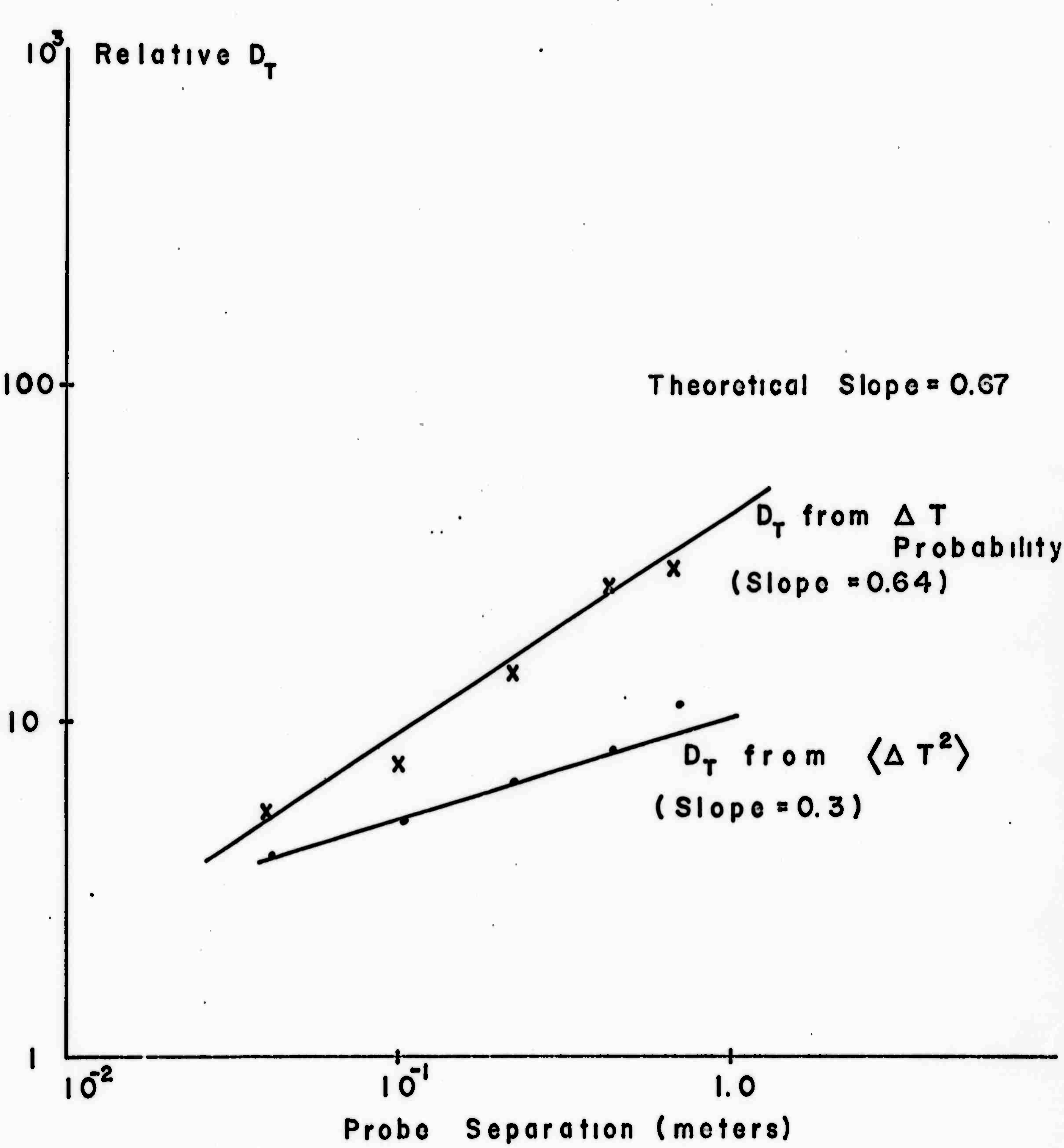

Probe
Separation
(meters)
1.0
10^{-1}
10^{-2}
Reciprocal Slope = 0.54
(Theoretical = 0.67)
1
10
100
Relative $\langle \Delta T^2 \rangle$

Figure 13



10^3
Relative D_T
100
10
1
10^{-2}
10^{-1}
1.0
Probe Separation (meters)
Theoretical Slope = 0.67
D_T from ΔT Probability
(Slope = 0.64)
D_T from $\langle \Delta T^2 \rangle$
(Slope = 0.3)

Figure 14

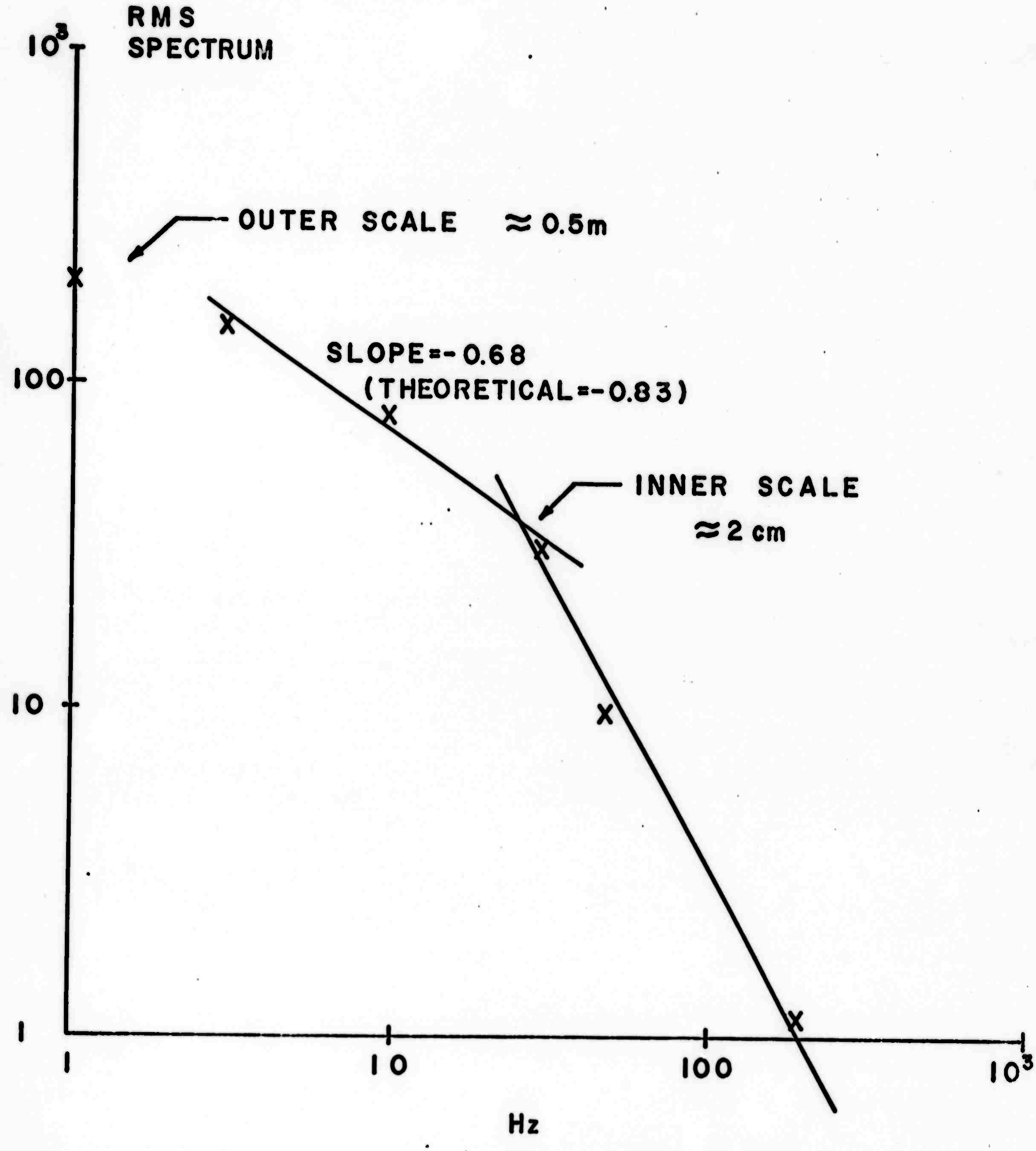
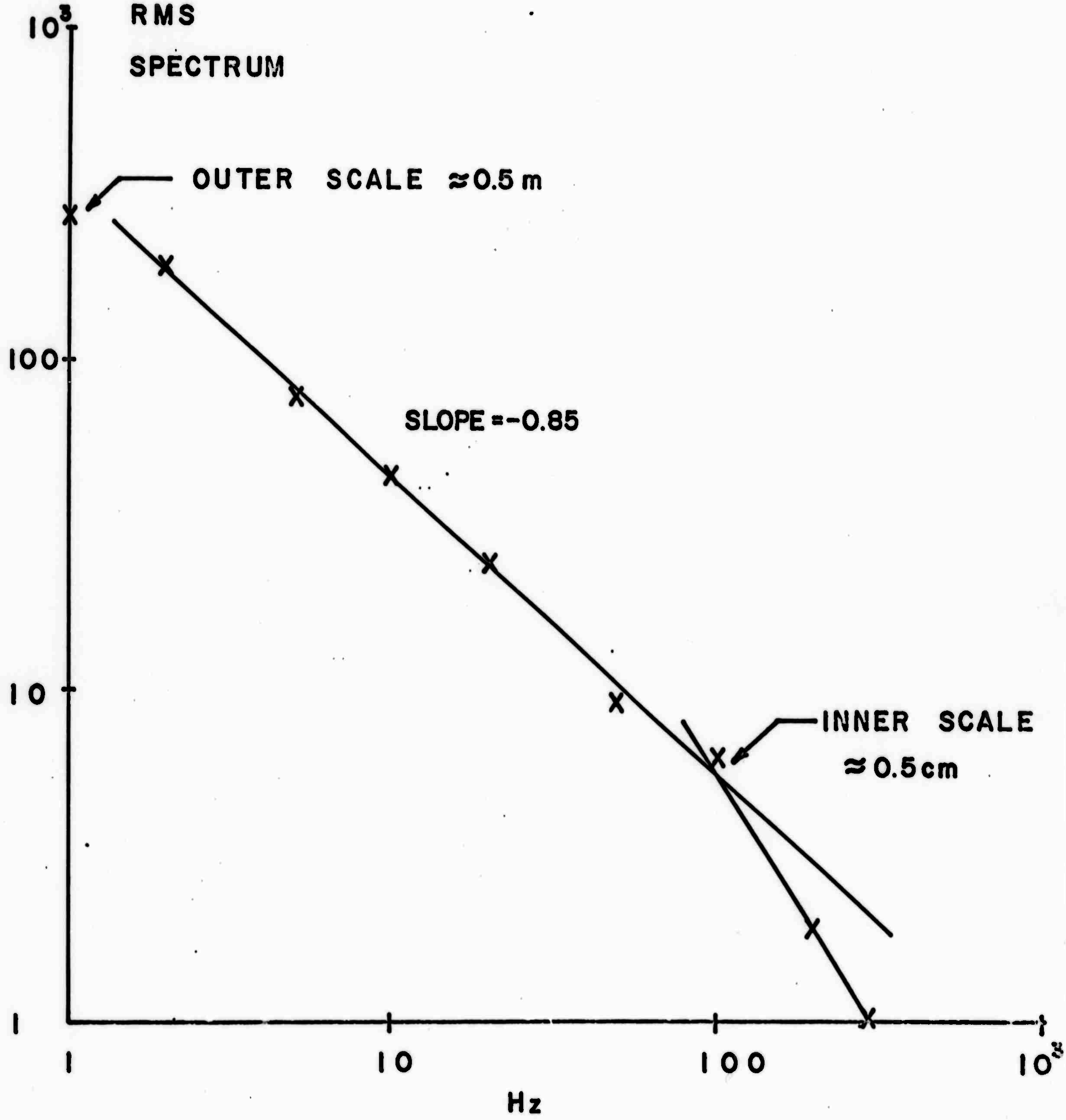

RMS SPECTRUM
10^3
100
10
1
OUTER SCALE ≈ 0.5m
SLOPE=-0.68
(THEORETICAL=-0.83)
INNER SCALE ≈ 2 cm
1
10
100
10^3
Hz

Figure 15a



10^3
RMS
SPECTRUM
OUTER SCALE ≈0.5 m
100
SLOPE =-0.85
10
INNER SCALE
≈0.5cm
1
1
10
100
10^3
Hz

Figure 15b

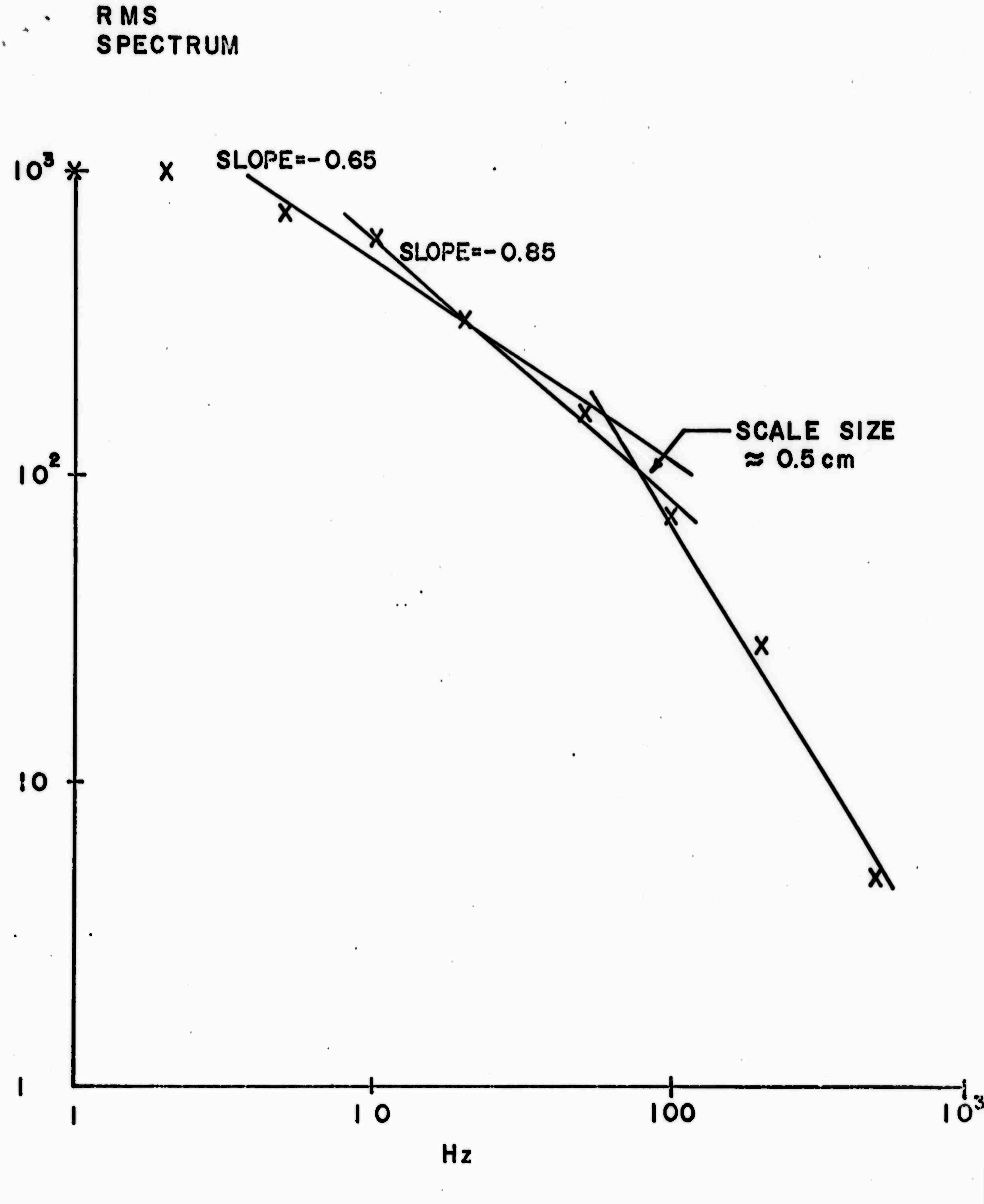

RMS
SPECTRUM
SLOPE=-0.65
SLOPE=-0.85
SCALE SIZE
≈ 0.5 cm
10^3
10^2
10
1
1
10
100
10^3
Hz

Figure 15c

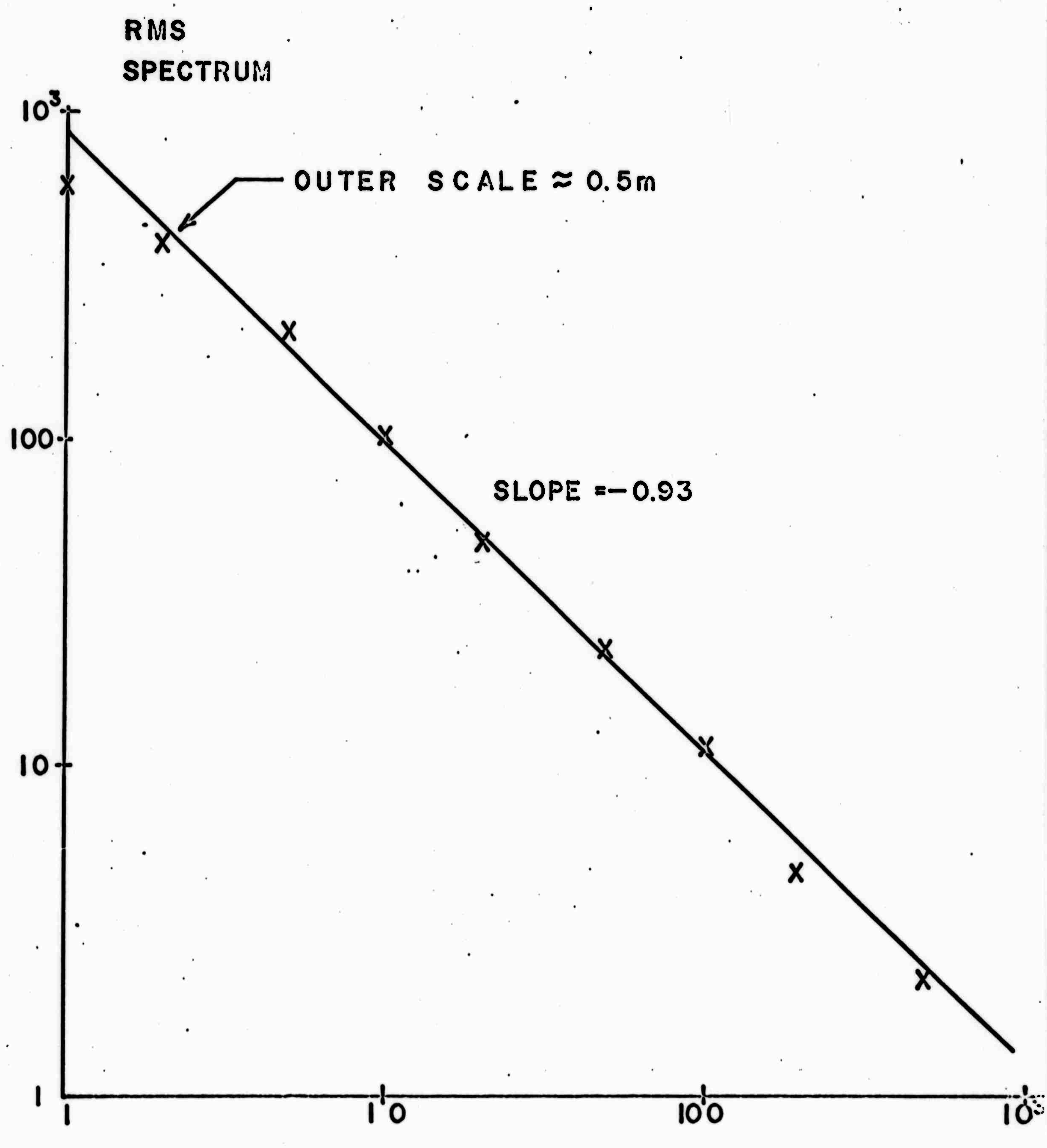

RMS
SPECTRUM
OUTER SCALE ≈ 0.5m
SLOPE =−0.93
10³
100
10
1
1
10
100
10³
Hz

Figure 15d

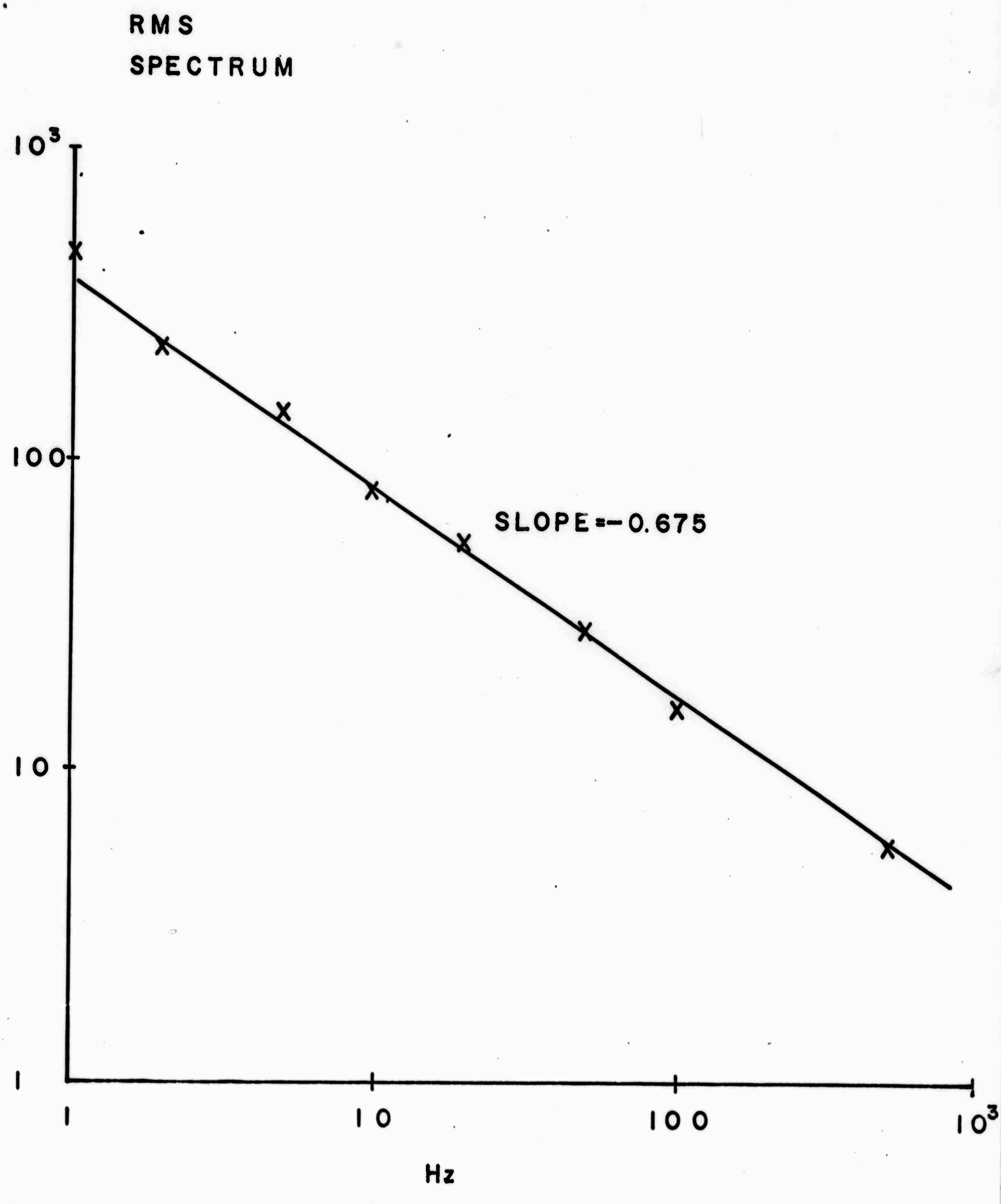


Figure 15e

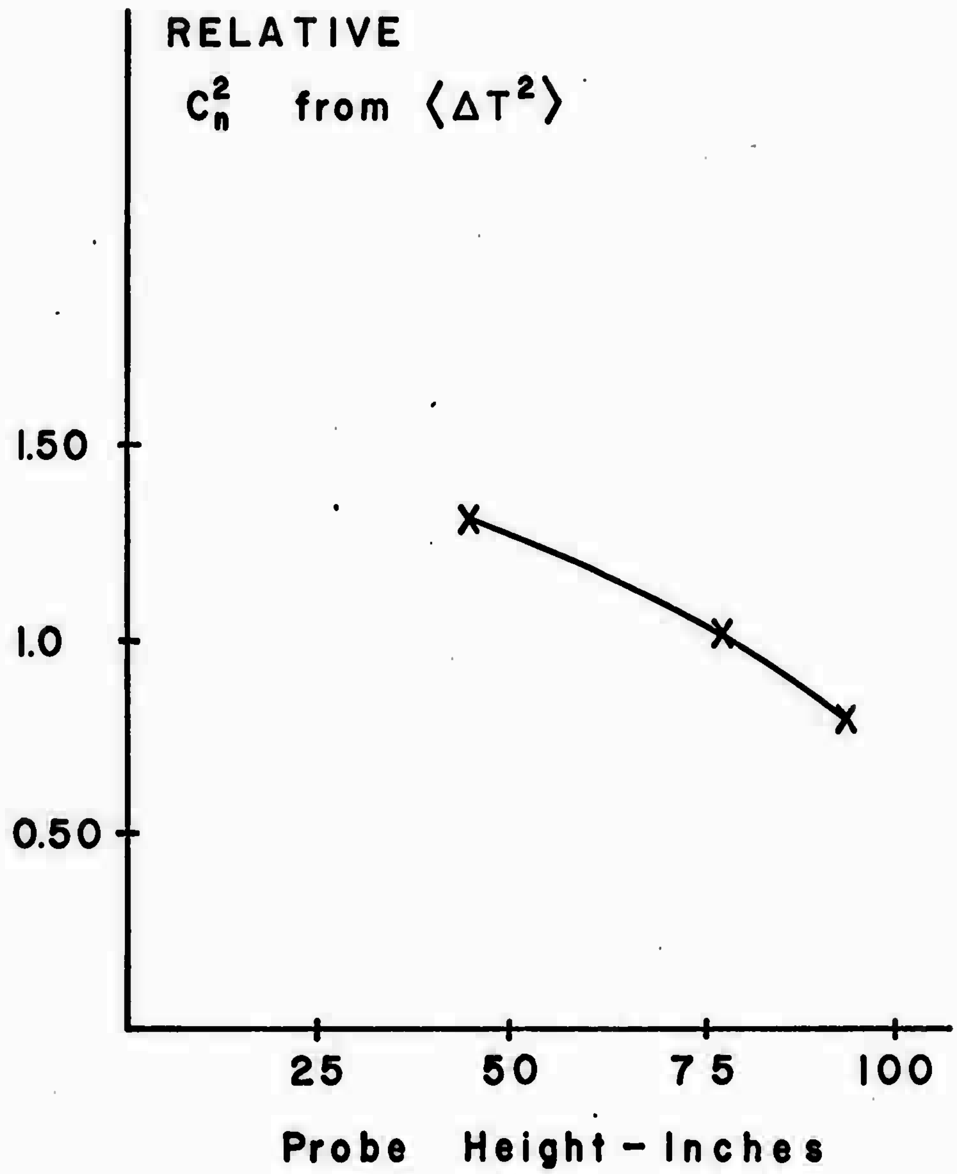

RELATIVE
C_n^2 from $\langle \Delta T^2 \rangle$
1.50
1.0
0.50
25
50
75
100
Probe Height - Inches

Figure 16

Unclassified

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13. ABSTRACT

During the annual period covered by ~~this~~ the report, a comprehensive, multiwavelength laser-beam propagation facility was operated over a horizontal, 1 mile path in order to investigate the adequacy of the commonly-used atmospheric model and to establish the wavelength-dependence of scintillations. The optical measurements included log amplitude variances, covariances, scintillation spectra, probability distributions, and receiver and transmitter aperture effects. The microthermal measurements included turbulence spectra, critical scales, and temperature probability distributions.

It was found that the inertial subrange model constitutes only an approximation to the true turbulence structure, and that the inner scale is often nonnegligible. The prevalence of quasi-discrete inhomogeneities in the refractive index structure constant was verified, and the consequent difficulty in relating nonoptical "strength of turbulence" measurements to actual scintillations is pointed out. In spite of these inadequacies in the atmospheric model, it was found that the unsaturated multiwavelength scintillations compared reasonably well with theoretical predictions when based on the turbulence as determined from scintillations of a short-path, portable laser. Also, there was no indication of saturation of longer wavelengths at low variances relative to those for visible wavelengths. These are other tentative conclusions are discussed in detail.

The follow-on program is described, during which a series of comprehensive measurements will be made to establish further confidence in the tentative conclusions. Following this, certain other details will be investigated.

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	ROLE	WT	ROLE	WT	ROLE	WT
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Infrared atmospheric transmission						
Turbulence scattering						
Atmospheric propagation						